



Further studies on age validation of Murphy's mackerel (*Trachurus symmetricus murphyi*).

New Zealand Fisheries Assessment Report 2013/14

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ISSN 1179-5352 (online)
ISBN 978-0-478-40549-1 (online)

March 2013



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EXECUTIVE SUMMARY

Beentjes, M.P.; Neil, H.L.; Taylor, P.R.; Marriot, P. (2013). Further studies on age validation of Murphy's mackerel (*Trachurus symmetricus murphyi*).

New Zealand Fisheries Assessment Report 2013/14. 38 p.

In this report we attempt to validate increment periodicity in otoliths of Murphy's mackerel (*Trachurus symmetricus murphyi*) based on the narrow-zone thin section ageing method, using a marginal state analysis, and the bomb radiocarbon procedure. In addition, we investigate the relationship between external corrugation/ring counts from whole otoliths and growth zones from transverse thin sections. Stable radio isotope studies were also carried out to look at the ambient environmental conditions experienced by individual fish throughout their life history.

A set of 480 otoliths collected from February 2005 to January 2006, mainly from JMA 7, and supplemented with a few juvenile otoliths from Chile, were used for both ageing methods. Comparison of mean length at age (narrow-zone method) for otoliths in this study, and those aged in 2002 indicate that the ageing protocol is consistent with the previous study. Both the external corrugations and rings were generally well defined and readability was considerably better than for thin sections. There were generally slightly more rings than corrugations recorded but they appear to be the same structure. The narrow-zone thin section method gave 1–35 growth zones compared to 4–18 corrugations/rings for the novel whole otolith method, and there was a poor relationship between the putative ages from these two methods (linear regression $R^2 = 0.08$). This poor correlation indicates that it is not feasible to convert ages (growth zones) estimated from whole otoliths to those from thin sections, or vice versa, with any degree of certainty, without a good representation of small fish in the sample. Corrugations/rings counts from whole otoliths tend to be less than those for thin sections but for the first six years the two methods seem to count the same structures, after which there are multiple thin section growth zones per corrugation.

The attempt to validate the narrow-zone thin section method using marginal state analysis proved to be inconclusive. The trend of an increase in the proportion of the wide marginal state in winter, as suggested by the 2002 study was not consistent with our data and it would be difficult to interpret any meaningful trend. Given the doubt associated with this validation of the narrow-zone thin section method, the whole otolith method may be equally as plausible. Other validation techniques such as mark and recapture of chemically tagged fish or captive rearing are required to validate ageing of Murphy's mackerel in New Zealand.

Validation of fish age estimates (from otoliths annuli counts) using the bomb radiocarbon relies on being able to detect the increase in $\Delta^{14}\text{C}$ concentration that is found in otoliths from fish growing during the years when nuclear weapons-derived ^{14}C was first appearing in the surface ocean waters (1955–1963). From radiocarbon analyses, conducted in 2005, the ages of three individuals of Murphy's mackerel could not be successfully validated as the otoliths tested had significantly enriched $\Delta^{14}\text{C}$ values within their cores. To understand this, information is required on the origin, migration, juvenile behaviour, and prey types. Most importantly we need to know $\Delta^{14}\text{C}$ values from cores of known mackerel coastal stocks, from prey types, and from New Zealand and South American estuaries and coastal waters. We also need to know residence within waters elevated in $\Delta^{14}\text{C}$.

Some valuable insights into the life histories of Murphy's jack mackerel were obtained from the stable isotope analyses. The temperatures in which these adult fish reside are consistent with that from the areas and depths they were caught. However, as juveniles these individuals resided in significantly warmer subtropical waters, at least prior to estimated age 7, probably outside of New

Zealand waters and did not reside in or migrate to cooler Pacific or New Zealand waters until after this time. It is suggested that individuals also reached maturity at about this same time.

1 INTRODUCTION

Age validation is a necessary step in developing a reliable technique for age estimation (Beamish & McFarlane 1983) and several different procedures can be employed (Campana 2001). In one case, daily increments have been validated for the *Trachurus symmetricus murphyi* otolith using oxytetracycline (Araya et al. 2001). However, there is no reliable validation available for annual increments from the international literature and, considering the complexity of structure in the otolith, only local validation can prove a relationship between annual counts and age. Age validation seldom produces an estimate of absolute age, but usually validates the periodicity of growth increment formation (Campana 2001). A validated method confirms both the frequency of growth increment formation in a given structure and that those workers reading the increments have interpreted them correctly.

1.1 Ageing based on otolith annual growth checks

An age-estimation technique for Murphy's mackerel (*T. s. murphyi*) has been developed by Taylor et al. (2002). The age estimations are the best currently available, but, there remains a level of uncertainty associated with this approach. The methodology is based on counts of growth zones from sagittae otolith transverse sections and was developed using the experience and contributions of workers elsewhere who have estimated ages for this and other mackerel species (Kaiser 1973, Carrera & Collantes 1978, Kochkin 1980, 1986, Shcherbich 1992, Horn 1993, Kochkin 1994), and for species of other genera with similar features and difficulties in the otolith structure (Wysokinski 1985, Shcherbich 1992, Paul et al. 2000, Paul & Francis 2002).

Ageing estimation and validation was carried out for the New Zealand species of jack mackerel (*T. declivus* and *T. novaezelandiae*) in the early 1990s (Horn 1993) and by comparison with Murphy's mackerel the growth check rings for the New Zealand species were relatively clear and easy to interpret. Validation for the New Zealand jack mackerel species was achieved by modal progression analysis of length and age frequency distributions. Similarly, Taylor et al. (2002) attempted to validate the estimated ages for Murphy's mackerel by tracking progression of strong year classes. Although this qualitative method provided some support for the ageing methodology, there was sufficient variability in the results to suggest that the ageing is not validated. One potential cause of the variability may have been errors in estimates of the proportion of the jack mackerel catch that is Murphy's mackerel, and hence in the resulting scaled length frequency distributions. The three species of mackerel are landed as aggregate JMA with the proportion of each species calculated from observer data, and consequently, the accuracy of the species proportions is dependent on the level of observer coverage. The method of validation by tracking strong year classes is more difficult in Murphy's mackerel than the New Zealand mackerel species because there are no juvenile length classes present. Thus, the bulk of the length frequency distributions are composed of large mature fish between about 46 and 54 cm FL (Taylor 2002) where growth in length is slight. Further, Murphy's mackerel appeared in New Zealand in the mid 1980s (Kawahara et al. 1988, Taylor 2002) and although a few juveniles have been found by observers and during research trawls, there is no evidence of any significant recruitment of juveniles to the New Zealand fishery. The absence of recruitment suggest that the stock is not self sustaining in New Zealand waters and may be part of an extensive trans-Pacific stock, which emigrated from the eastern South Pacific near the coast of South America. Hence, we might expect growth to be affected by different environmental conditions between the eastern and western Pacific, and this may have contributed to the complex structure of the otolith and the difficulty in interpreting growth checks.

Age and growth studies of *T. s. murphyi* in South America have included ring counts from whole otoliths observed through transmitted light (Kaiser 1973), and dark zone counts from thin sections – both the rings and zones were interpreted as annual growth checks. The resultant ages were considerably less than those of Taylor et al. (in press). In both cases the maximum ages were about 10 years, compared to ages over 35 years for Taylor et al. (in press), and maximum ages of 28 and 23 years for *T. novaezelandiae* and *T. declivus*, respectively (Horn 1993). Generally, counts of annual increments from whole otoliths (external corrugations or rings counts) underestimate age (Beamish 1979, Campana 2001). The benefit of using counts from whole otoliths as a basis for age estimation, is the lower processing costs compared with sectioned otoliths.

Taylor et al. (in press) also carried out a preliminary marginal state analysis in an attempt to validate the periodicity of annual increments in the structure of the otolith. Marginal state analysis is similar to the “edge analysis” of Campana (2001), but less rigorous than a marginal increment analysis. They used the same otoliths read for age estimations, to provide information on the validity of the narrow-zone technique they developed. A single peak in the proportion of otoliths with a wide opaque margin over the winter months suggested the production of a single opaque margin in *T. s. murphyi* otoliths each calendar year, thereby supporting adoption of the narrow-zone interpretation. Unfortunately, otoliths were not available for examination over the entire year, so no peak in the production of an opaque zone was identified. The only conclusion that could be drawn was for a possible increasing trend in the proportion of otoliths with wide or opaque margins from January to April/May, and a possible decline from October to December. However, these results suggest that a marginal state analysis can be carried out on *T. s. murphyi* otoliths, although a marginal increment analysis, which requires measurements of the width of the margin, was unlikely to be successful because of the difficulty of determining the cut-off between the opaque and translucent zones. With adequate sampling throughout a single year, a marginal state analysis may provide validation for the formation of annual opaque zones.

1.2 Bomb radiocarbon method for age validation

A recently developed (early 1990s) age validation procedure is based on levels of radiocarbon in the ocean, known to have changed over recent decades. Nuclear testing in the Pacific region introduced a pulse of ^{14}C into the atmosphere between 1950 and 1970, which entered the ocean and quickly became incorporated in the carbonate of hard tissues (coral skeletons, fish otoliths) in concentrations proportional to those in the water column. The first studies used otolith core material to position a fish somewhere on the time-line of radiocarbon levels, thus giving it a birth-date, and allowing comparison with an age determined by growth zone count.

Validation of fish age estimates based on counting otolith growth-bands relies on being able to detect the increase in ^{14}C concentration that is found in otoliths growing during the years when nuclear weapons-derived ^{14}C was first appearing in the surface ocean waters (1955–1963). Previous work (Kalish 1993) has established the shape of the otolith bomb-carbon response curve for surface dwelling fish in the vicinity of New Zealand. By measuring the ^{14}C within a single otolith core it should be possible to associate this specific part of the otolith with a specific year on the bomb-carbon response, provided the catch date of the otolith is known. By counting the growth bands laid down over time it becomes possible to estimate a year (“age”) for the otolith core.

The process should be repeated for a number of suitable otoliths to allow the reliability of the values found to be assessed. This procedure is in line with the standard procedure developed by Kalish, and is considered appropriate for otoliths from fishes living in surface waters. Useful accounts are given in most of the relatively few published studies (Kalish 1993, 1995, Kalish et al. 1996, Campana 1997,

Campana & Jones 1997, Kalish et al. 1997, Morison et al. 1999, Baker & Wilson 2001, Campana et al. 2002).

A number of conditions must be met for a successful result from this work:

- The species spends a significant part of its life cycle in near surface waters.
- The specimen's birth year is within the extremes of the bomb curve (approximately 1955–1975).
- The specimen's annual increments are identifiable.
- The specimen's otolith size is sufficient to obtain up to five samples.
- Sufficient precision of ^{14}C measurements is possible to reliably find g , the units of growth bands per year.

This procedure was used at NIWA by Paul et al. (2000) to validate age estimates for rubyfish (*Plagiogeneion rubiginosum*) and bluenose (*Hyperoglyphe antarctica*) at the time of the jack mackerel analyses included in this study.

1.2.1 Stable isotopes

Oxygen and carbon isotopes have a long history of interpretation and use. In otoliths, stable isotopes have been used to provide information on environmental variation (i.e., habitat, diet, temperature, depth, metabolic history and migration) that an organism has experienced throughout its life history (e.g., Radtke et al. 1987, Kalish 1991, Northcote et al. 1992, Thorrold et al. 1997, Schwarcz et al. 1998, Begg & Weidman 2001, Gao et al. 2001). Insight into the relationship between environmental conditions and the response of fish populations is highly desirable for fisheries management (e.g., Campana et al. 1995, Roelke & Cifuentes 1997, Campana & Thorrold 2001)

Stable isotope chemistry is based upon the chemically inert nature of otoliths and their continuous growth through life; they accumulate and retain a life-long record of the internal and external environment of the fish. Oxygen isotopes ($\delta^{18}\text{O}$) are deposited close to isotopic equilibrium with environmental water, hence the environmental temperature in which a marine organism lived can be determined (e.g., Grossman & Ku 1986, Kim & O'Neil 1997, Campana 1999). Carbon isotopes ($\delta^{13}\text{C}$) are considered to be deposited in equilibrium with the dissolved inorganic carbon (DIC) incorporated into the endolymph from blood plasma (e.g., Kalish 1991, Thorrold et al. 1997, Schwarcz et al. 1998, Begg & Weidman 2001). Carbon isotope data may provide information on growth and metabolic rates, and diet.

The location of fish within a region and a specific habitat is important for defining $\Delta^{14}\text{C}$ values. Marine-derived $\Delta^{14}\text{C}$ values vary significantly with latitude, circulation, depth and depth of penetration of the bomb carbon signal, among other factors. In the absence of information on fish habitat at the time of otolith growth zone formation, it would be difficult to assign a year of formation to an individual $\Delta^{14}\text{C}$ value (Campana 1999). Therefore, in this study we examined stable isotopes in order to elucidate otolith chronology.

1.2.2 Oceanography of the Snares region

The jack mackerel used in the stable isotope and bomb radiocarbon studies were sourced from the Snares Shelf. The continental shelf off southern New Zealand is relatively wide. The Snares platform is a relatively flat feature shallower than 250m, which to the southwest plunges down the precipitous margin of the Solander Trough to depths of more than 3000 m. To the southeast the Snares platform merges with the extensive 600–1000 m Campbell Plateau which comprises a number of broad rises and depressions (Neil et al. 2004) (Figure 1). In this region off southern New Zealand there are several water masses and surface currents (Figure 1).

North of the Subtropical Front (STF), the surface waters are highly saline, nutrient-depleted, warm subtropical water sourced from the north, whereas south of the STF surface waters have lower salinity, and comprise nutrient-rich, cool Subantarctic surface water (SASW) derived from south of New Zealand. These surface water masses meet across the STF. The STF in the New Zealand region crosses the Tasman Sea at approximately 43°S, approaches New Zealand at the latitude of Fiordland (Stanton & Ridgway 1988), before diverting southward around New Zealand, bathing the Snares Platform region, before turning along the continental margin off the south-eastern South Island, turning east along Chatham Rise at approximately 43°S, following approximately the 15°C isotherm in summer. The STF is a complex and irregular frontal zone comprising large meanders and eddies, in the Tasman Sea it is free to meander while to the east of New Zealand it is constrained by easterly flows along the flanks of Chatham Rise (Chiswell 1994). South of New Zealand, constrained by the Campbell Plateau, the Subantarctic Front (SAF) separates subantarctic from circumpolar surface waters while to the far north the Tropical Front separates tropical waters from subtropical waters.

Antarctic intermediate water (AAIW), a major northward-spreading water mass, occurs immediately below surface water masses at depths of approximately 600–1450 m. Circumpolar deep water (CPDW) underlies AAIW down to the seafloor in this region.

1.3 Objectives of this report

In this report we examine the feasibility of validating increment periodicity in otoliths of *T. s. murphyi* and the ageing method defined by Taylor et al. (2002) using a marginal state analysis, and the bomb radiocarbon procedure. In addition, we investigate the relationship between corrugation/ring counts from whole otoliths and counts from transverse thin sections using the method of Taylor et al. (2002).

2 METHODS:

2.1 Otoliths used in growth zone interpretations

Jack mackerel catches have been sampled by the stock monitoring programme from October 2003 to the present (October 2006) to determine more accurately the proportion of the jack mackerel catch that is made up by each of the three species (*T. s. Murphyi*, *T. declivus*, and *T. novaezelandiae*). Up to seven samples per month were collected, and the programme attempted to sample all months of the year. In addition, from January 2004 onward, otoliths were taken, and length, weight and sex of fish were recorded from a representative size range of Murphy's mackerel with the aim of sampling about 50 fish per month. Most sampled landings were from JMA 7 with a few from JMA 1. The bulk of the sampling was carried out by NIWA staff in factories in Nelson and Motueka, with a few landings from Christchurch and Greymouth. Otoliths were stored dry in labelled paper envelopes and associated data are held in the NIWA *age* and *market* databases. We selected otoliths sampled between February 2005 and January 2006, which included all months except July (Table 1). A total of 480 otoliths were collected, and of these 94% were from JMA 7 and 6% from JMA 1 (Table 1). In addition, because the New Zealand fishery captures only adult Murphy's mackerel, otoliths from seven juvenile Murphy's mackerel from Chile (22–38 cm) were included to widen the length range of our otolith set. The same otoliths were used for whole readings of corrugations and rings, thin section growth zones, and marginal state analysis. We did not separate otoliths by sex as there is uncertainty in growth characteristics between males and females and Taylor et al. (in press) recommended that future analyses of growth combine the sexes.

2.2 Surface corrugations and ring counts from whole otoliths.

Before otoliths were processed and prepared as thin sections, one or both whole otoliths from each fish were examined using a binocular microscope under reflected and transmitted light. The distal surface (side without the sulcus), mid way between the posterior and anterior ends of the otolith, was found to be the most useful location for tracking both corrugations and rings. Under reflected light, corrugations were read from the primordium (nucleus) toward the ventral edge without reference to the fish length. Based on the location of the first zone read from thin sections by Taylor et al. (2002), the first corrugation was nominally considered to be about 0.5 mm out from the nucleus where the surface begins to flatten out. The second and third were about 0.3 mm out from the first and second, respectively. The corrugations were most clearly defined mid way between the primordium and the ventral edge, and they became progressively narrower at the extreme ventral edge where they tended to fold together. Attempts to examine the corrugations on otoliths that had been immersed in oil and/or using transmitted light proved to be less effective and dry otoliths observed using oblique reflected light was found to be the most effective method. When whole otoliths were observed under transmitted light, dark rings or zones could be observed that appeared to correspond to the major corrugation troughs. Immersing the otolith in oil sometimes improved the clarity of the rings. The otolith was given an overall reading score from 1 to 5. (1 is excellent and 5 is virtually unreadable) for the combined corrugation and ring count because clarity tended to be correlated. A single reader estimated the number of corrugations and rings.

Counts of corrugations and rings were compared using linear regression.

Micrographs were taken of examples of otoliths with clear corrugations and rings and these were compared to thin sections for the same otolith.

2.3 Preparation of otolith thin sections

For otoliths used in the thin sections and marginal state analyses, processing and reading protocol followed the method adopted by Taylor et al. (2002). Otoliths were embedded in Araldite (K142) resin and cured at 50°C for 24 hours. The resin blocks were sectioned transversely through the otolith primordia using a Struers Accutom-2 low speed saw with a diamond edged wafering blade. The cut surface of the block was then polished using progressively finer carborundum paper (300–1200 grit).

2.4 Reading zones from thin sections

Alternating translucent (light) and opaque (dark) zones were evident in otolith thin sections read with a bright field stereomicroscope under transmitted light (magnification 40). The number of complete opaque zones was counted (i.e., opaque zones with translucent material on the outside) adopting the ‘narrow-zone’ protocol of Taylor et al. (2002), and these were assumed to be annual growth checks or annuli. The Protocol otolith set was used to ensure that the readers were interpreting the otoliths in the same way.

Reader 1 read all otoliths, whereas reader 2 read a subsample of the otoliths to check for consistency between readers. An agreed zone count was then determined for the total set. Counts between readers were compared using linear regression.

To check for consistency with previous ageing the mean lengths at age for otoliths in this study were compared with those aged in 2002 (Taylor et al. 2002).

2.5 Marginal state analysis

Marginal state readings were obtained using a bright field stereomicroscope under transmitted light (magnification 100). The marginal state (narrow, medium, or wide) was tabulated by the month in which the otolith was collected. The proportion of wide state otoliths was plotted by month. Marginal states are defined as follows:

- Narrow: a margin made up mainly of translucent material, with a hairline of opaque material that is continuous across most/all of the extreme margin.
- Medium: a margin exhibiting a wider opaque zone than for a narrow margin with no/very little new translucent material.
- Wide: a margin made up of a wide opaque zone, with no new translucent material present.

2.6 Bomb radio-carbon procedure

2.6.1 Otolith carbonate sampling for stable isotopes and radiocarbon

2.6.1.1 Sectioning

One otolith from each of the selected three *T. s. murphyi*, collected in 1989 from the Snares shelf during a research trawl survey on the Amaltal Explorer (trip AEX8902) (Figure 1) were prepared for sampling. For each specimen, a series of transverse sections containing the central region of the otolith were cut with a Struers Accutom II saw and mounted on a glass microscope slide. Two steps were then followed: sampling the otolith core for radiocarbon, and sampling across the otolith for a more detailed sequence of stable isotope values.

2.6.1.2 Core and cross-section sampling

Micro-sampling was done using a New Wave™ micromill. Images of the otolith sections were analysed and the core region identified. Approximately 1 mg of material was removed from the core region of each otolith. This material, in the form of milled powder, was transferred to a sterile vial. The milling bit was cleaned between each sample to prevent contamination.

Samples were extracted in a similar manner for analysis of the stable isotopes $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$. Smaller sample sizes are required for this analysis (approximately 30 μg). Swathes parallel to the plane of growth were milled along a transect across the otolith from the core to the otolith's edge. Each swath across the otolith comprised a single sample.

2.6.2 Stable isotope analysis

Powder samples were reacted with two drops of 100% H_3PO_4 for 10 minutes at 75°C in a Finnigan MAT automated individual carbonate (Kiel) reaction device. Oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) isotopes were determined from the resultant liberated CO_2 analysed by a Finnigan MAT 252 mass spectrometer. Concurrently run carbonate standards (NBS-19) had an internal precision of $\pm 0.04\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.08\text{‰}$ for $\delta^{18}\text{O}$, and an external precision (between runs) of $\pm 0.8\text{‰}$; results are reported relative to vPDB (Table 2). $\delta^{18}\text{O}$ results were used to estimate sea water temperatures from the revised calibration equation of Kim & O'Neil (1997) based on inorganic aragonite (Campana 1999):

$$T^{\circ}\text{C} = \frac{\delta \text{ oto} - \delta \text{ w} - 3.71}{-0.206}$$

where T = ambient seawater temperature, $\delta \text{ oto}$ = $\delta^{18}\text{O}$ of otolith aragonite, and $\delta \text{ w}$ = ambient $\delta^{18}\text{O}$ seawater. In light of the lack of measured $\delta \text{ w}$ from the Snares region ambient seawater is estimated using the salinity correction from the relationship of Savin et al. (1985):

$$\delta \text{ w} = 0.687 \times S - 23.74$$

where S = mean salinity values estimated for shallow water around southern New Zealand. Salinity is derived from CTD (conductivity-temperature-depth) stations near Snares Platform from NIWA CTD Voyage 3006, Inflow 1, April 1993, and NIWA CTD Voyage 3046 (TAN9806), Subantarctic 1, May 1998. These sections were also used for the estimations of individual depth (Figure 2). Seawater temperatures were also estimated using the two available measured $\delta \text{ w}$ values for Subtropical waters from east coast of New Zealand: $\delta \text{ w} = 0.3$ (Schmidt et al. 1999) and Galapagos Islands west of South America: $\delta \text{ w} = 0.4$ (Wellington et al. 1996).

2.6.3 Radiocarbon analyses

The carbonate removed from the otoliths was converted to graphite using standard methods employed at the Rafter Radiocarbon Laboratory. The powdered carbonate was first converted to CO_2 gas by reacting it with phosphoric acid in a vessel connected to a vacuum line. The evolved CO_2 passed through a dry-ice/alcohol cold-trap to remove water vapour and condensable vapours. It then was frozen in a cold trap at liquid nitrogen temperature to enable non-condensable vapours to be pumped away. The purified CO_2 was next converted to graphite by reducing it with hydrogen at 750°C over a catalyst consisting of fine iron powder. The resulting mix of graphite and iron was pressed into a 1 mm diameter hole in an aluminium capsule for measurement with the AMS particle accelerator.

The $^{14}\text{C}:^{13}\text{C}$ ratios were corrected for chemical isotopic fractionation effects by determining the $\delta^{13}\text{C}$ for each sample by stable isotope mass spectrometry, then normalising the measured $^{14}\text{C}:^{13}\text{C}$ ratio to a standard $\delta^{13}\text{C}$ of -25‰ . The $^{14}\text{C}:^{13}\text{C}$ ratios for each sample were calibrated against a similar measurement using a sample of NBS standard oxalic acid (HOx-I). Results of the measurements are given as $\Delta^{14}\text{C}$ (Karlen et al. 1964, Stuiver & Polach 1977). Included in the calculation is a correction for the decay that has occurred in the oxalic acid standard since its reference year of 1950. Thus, the form of $\Delta^{14}\text{C}$ used represents the absolute ^{14}C activity of the sample.

2.6.4 Matching carbonate sample positions with growth zone positions

Electronic images were made of the thin section for each otolith on which the growth zones had been counted, and the thicker sections (from the paired otolith) from which the carbonate samples had been taken for stable isotope and radiocarbon analyses. These were overlain, the position of the drill tracks for carbonate samples were clearly visible, and the sets of potential growth zones incorporated in each carbonate micro-sample were estimated (Figure 3, Tables 2 and 3).

3 RESULTS

3.1 Reading growth zones from otoliths

3.1.1 Whole otoliths

A total of 462 otoliths (out of the original 487) (Table 1) had corrugation counts, and 463 had ring counts. Photomicrographs of the distal surface of a whole otolith under reflected and transmitted light show how both corrugations and rings were identified (Figure 4). Both the corrugations and rings are generally well defined, particularly those midway between the primordium and ventral edge. The rings appear to correspond to the troughs that lie between the corrugations and appear as dark lines using transmitted light. The corrugations have three-dimensional structure and are accentuated by the contrast of shadow and light (Figure 4).

About two-thirds of otoliths had a readability of 3 and a quarter a readability of 2. (i.e., 6% for 1, 24% for 2, 59% for 3, 10% for 4, and 2% for 5). There is considerable variation in the number of both corrugation and ring counts for a given length, and without the juvenile otoliths from Chile included in the dataset, the slope of the line relating length to counts would be close to zero (Figures 5, 6, 7, and 8). Ring counts overall were slightly greater than those of corrugations, indicating that there may be internal structure that is not apparent on the surface (Figures 9 and 10). However, minimum (4) and maximum (18) counts were the same for both methods.

3.1.2 Thin section zones

A total of 469 otoliths thin sections (out of the original 487) viewed using transmitted light were assigned an agreed number of zones using the narrow-zone method (Taylor et al. 2002) (see Figure 4). The opaque dark zones appear to be well defined in some locations and obscure in others. More than three-quarters of the read otoliths were ranked as difficult to read (4), and about a fifth with average readability (3) (i.e., 0% for 1, 0.2% for 2, 20% for 3, 79% for 4, and 1% for 5). There was, however, generally good agreement between the two readers with a slope approaching 1.0, and the model explained 83% of the between reader variance (Figures 11 and 12). There is considerable variation in the number of zones for a given length, and, like the whole otolith analysis, without the juvenile otoliths from Chile included in the dataset the slope of a trend line fitted to this data would be close to zero (Figures 13 and 14). Comparison of mean length at age (i.e. zones) for otoliths in this study, and those aged in 2002 (Taylor et al. 2002), indicate that the ageing method is consistent with the previous study (Figure 15). Minimum and maximum ages were 1 and 35 years, respectively.

3.1.3 Comparison between whole otolith and thin section counts

Thin sections were qualitatively less readable than whole otoliths and there were generally considerably more thin section zones than corrugations and rings (Figures 16 and 17). For comparison a micrograph of a thin section is shown (see Figure 4) with the growth zones marked and also those corresponding approximately to corrugations (approximately because corrugations were counted on whole otoliths and not thin sections). The two methods place the first five zones in about the same position, but thereafter the differences become increasingly greater. There is a poor correlation between zones and corrugations, and zones and rings ($R^2 = 8\%$ for both), reflecting the high degree of variation inherent in both ageing methods, the difference between the whole and sectioned otoliths, and the paucity of otoliths from fish less than 45 cm in which growth is relatively fast (Figures 16 and 17). This poor correlation indicates that it is not feasible to convert ages estimated from whole otoliths to those from thin sections, or vice versa, with any degree of certainty, and particularly without a good representation of small fish in the sample.

3.1.4 Marginal increment analysis

A total of 462 otoliths were examined for marginal state and categorised as having a margin that was narrow, medium or wide. There were no otoliths collected in July and the sample size was small for May and October compared to the other months (Figure 18). The proportion of otoliths with wide margins showed a period of sharp decline in February, and again in October/November. For the other months the proportion was between 30 and 49%. There does not appear to be a clear trend in the proportion of otoliths with wide margins over a 12 month period.

3.2 Bomb radiocarbon

3.2.1 Information from isotope analyses

Marine fish otoliths are reported to range in value from -2 to $+4\%$ for oxygen isotopes, with carbon isotope values ranging from -9 to $+1\%$ (Romanek et al. 1992, Campana 1999). The $\delta^{18}\text{O}$ values of otoliths of *T. s. murphyi* ranged from 0.1 to 1.8% , whereas the $\delta^{13}\text{C}$ values ranged from -5.3 to -1.9% (Table 2). Values of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ move rapidly toward greater enrichment as samples progress from the core to the outer edge of the otolith (Figure 19).

3.2.1.1 Oxygen isotopes

Oxygen isotopes in otolith aragonite are deposited in, or very near to, equilibrium with the ambient water hence fish otoliths can be used to reconstruct temperature regimes. Otolith-predicted temperatures of the adult *T. s. murphyi* were based on mean salinity values for the Snares region in order to derive the isotopic composition of the water at the time of otolith formation (see Figure 2). Mean salinity values for shallow waters of 34.7 and 34.8% were used to derive the temperature. As the provenance of young *T. s. murphyi* is unknown, otolith-predicted temperatures were based on the only available values of the isotopic composition of the subtropical water, near east coast New Zealand and the Galapagos Islands.

Temperatures range from an estimated 17.5 – 19°C at the core of the jack mackerel *T. s. murphyi* otoliths to 9 – 12°C at the outer edge, although there is a spread in the population through the temperature decline (Table 2, Figure 20). The average or persistent residence depth of the adult *T. s. murphyi* fish can be determined from these predicted temperatures using temperature profiles for the Snares region. Depth ranges of approximately 100 – 300 m are consistent with trawl data for these adult individuals. Core values also imply depth distribution that is consistent with surficial subtropical waters (Figure 20).

3.2.1.2 Carbon isotopes

Carbon isotopes are generally understood to be deposited under non-equilibrium conditions, largely controlled by the endolymph from blood plasma (e.g., Kalish 1991, Schwarcz et al. 1998). Hence the metabolic rate of the fish, the diet of the fish and the dissolved inorganic carbon (DIC) of marine waters influence carbon isotopes. In the absence of local $\delta^{13}\text{C}$ measurements for DIC from southern waters, we use data from GEOSECS site 282 (Kroopnick 1985) to compare with our otolith values. Site 282 is south of New Zealand and as such is as closely comparable as possible (given available data) to that expected within this study region. DIC values of 1.5 – 2% are reported for shallow waters (less than 500 m).

All measured $\delta^{13}\text{C}$ values for *T. s. murphyi* are depleted with respect to DIC, with core values depleted by up to 7 ‰. Values are progressively less depleted towards the outer edge of the otoliths, although still depleted by at least 3.5‰ from DIC (Table 2, see Figure 19).

3.2.2 Information from radiocarbon analyses

The $\Delta^{14}\text{C}$ for each otolith sample, together with the growth year inferred from the zone count (at one zone per year) are shown in Table 3. Figure 21 shows $\Delta^{14}\text{C}$ plotted against the otolith-core $\Delta^{14}\text{C}$ curve for snapper caught off the east coast of the North Island of New Zealand (Kalish 1993). This curve is included to provide a reference for the change of surface water $\Delta^{14}\text{C}$ with time. Snapper live in the top few hundred metres near the surface where almost complete mixing of the water takes place. Organisms confined to the surface region will very likely be in isotopic equilibrium with the dissolved inorganic carbonate (DIC) as far as ^{14}C is concerned, since the DIC is fed into the food chain through photosynthesis by phytoplankton. For this reason, regardless of the pathway taken by carbon from DIC to otolith carbonate, the snapper otolith provides a proxy of the DIC $\Delta^{14}\text{C}$ in the ambient water.

The first step was to measure $\Delta^{14}\text{C}$ in samples taken from the otolith cores to check that they were born before or close to the onset of bomb-carbon, as indicated from the birth year inferred from zone counting. Somewhat surprisingly, in all cases the ^{14}C level was significantly more enriched than expected for marine values of juveniles residing near the surface. Subsequently the remainder outwards from the core (adult section) of JMM2 was analysed and the resultant value measured is in agreement with the predicted value of surficial $\Delta^{14}\text{C}$ for the 1980's. It needs to be remembered that this data point represents the average of a large group of growth zones (Figure 21).

4 DISCUSSION

4.1 Reading growth zones from otoliths

Two methods of counting growth zones from otoliths of Murphy's mackerel were carried out and the results compared. The previously used thin section method gave ages between 1 and 35 compared to 4 and 18 for the novel whole otolith method and there was a poor relationship between the assumed ages from these two methods. There are two possible reasons for the low correlation between the estimated ages derived from these two methods. Firstly, for both methods there was very little difference in the mean length of fish over a large presumed age range and growth appears to be very slow after the fish has reached about 50 cm. Secondly, there are few otoliths from large fish (over 60 cm), or from small fish where growth is fast and where we would expect to observe a stronger correlation between length and growth zones. Given the virtual absence of juvenile Murphy's jack mackerel in New Zealand waters, it is unlikely that future analyses can incorporate otoliths from small fish and these would need to be sourced from Chile. The large, older fish that were once common in the fishery are also unlikely to return. Hence, converting age estimated from one method to another is unlikely to be either accurate or practical. Counts of external corrugations or rings are generally lower than equivalent growth zones determined from thin sections (Beamish 1979, Campana 2001). Studies on Pacific hake (*Merluccius productus*) showed that counts are similar at smaller sizes and ages before the growth slows, after which allometric changes in the shape of the otolith render thin section counts more reliable (Beamish 1979). For Murphy's mackerel this may also be the case – the first six counts from both whole otoliths and thin sections appear to be counting the same growth zone, however, after this there are multiple thin section zones per corrugation (see Figure 4).

Corrugations and/or rings counted from whole otoliths appear qualitatively to be more readable than zones from thin sections, possibly because there are fewer to read. The difference between rings and corrugations is small and probably results from a combination of reader error and the fact that rings are more visible than the corrugations. Further, the count of corrugations/rings are also closer to, but greater than, the ages obtained for Murphy's mackerel from Chile where the maximum age was 12 years corresponding to fish 63 cm (Kaiser 1973) and 10 years for fish 52 cm (Kochkin 1994). Indeed the corrugations appear to be more closely associated with the zones estimated using the clumping method of Taylor et al. (in press), in which the annuli are described as being sculpted. The narrow-zone was chosen over the clumped-zone method by Taylor et al. (in press) because of the good clarity of the growth zones and because the resultant ages were similar to those estimated for *T. declivus* (Horn 1993). It seems incongruous that the same species of fish would grow so much slower and live to three times as old in New Zealand as in Chile, but this may be partly a result of warmer water and more productive waters on the west coast of South America and elsewhere in the Pacific. The results of the stable radio isotope study (see below) suggest that before the estimated age of seven, (thin section), Murphy's mackerel reside in warmer subtropical waters. This is consistent with the absence of juveniles in New Zealand waters and a potentially faster growth elsewhere.

The attempt to validate the narrow-zone thin section method using marginal state analysis proved to be inconclusive. The trend of an increase in the proportion of the wide marginal state in winter, as suggested by Taylor et al. (in press) was not consistent with our data and it would be difficult to interpret any meaningful trend. Attempts by Taylor et al. (in press) to validate the narrow-zone ageing method by tracking age classes from age frequency distributions gave mixed results, confounded by poor data on jack mackerel species proportions, and they suggest that this is not strong evidence of validation. The bomb radiocarbon validation also proved to be inconclusive (see below). Given the doubt associated with this validation of the narrow-zone thin section method, the whole otolith method may be equally as plausible. However, counts of annual increments from whole otoliths (external corrugations or rings counts) generally tend to underestimate age (Beamish 1979, Campana 2001) for two reasons. Firstly, as growth slows down the zones are laid down much closer together and are less apparent from external examination. Secondly, as the fish matures there is a shift in deposition of otolith material from the dorso-ventral and anterior-posterior planes of growth to the proximal-distal plane, i.e., the otolith becomes broader. Hence, when viewing old otoliths whole, many of the edge zones are less apparent on the distal surface. In contrast, on transversely sectioned otoliths both the dorso-ventral and proximal-distal planes of growth can be observed and this is where the recent zones have generally been deposited. Other validation techniques such as mark and recapture of chemically tagged fish or captive rearing are required to validate ageing of New Zealand Murphy's mackerel.

4.2 Bomb Radiocarbon

4.2.1 Radiocarbon

To interpret the observed $\Delta^{14}\text{C}$ levels, some consideration must be given to the origin of the otolith carbon. Given the depth data, *T. s. murphyi* should follow the simple relationship between ^{14}C in the otolith and the ambient water that characterises snapper. However, when the depth data are combined with the ^{14}C data it quickly becomes apparent that the simple relationship that characterises snapper does not apply to the cores of juvenile *T. s. murphyi* analysed here.

The ^{14}C levels found in the otolith cores are too enriched for marine water at the residence depths. A possible mechanism to explain these significantly enriched values would be for the juvenile *T. s. murphyi* to be exposed to enriched ^{14}C levels through either residence in, or predation on another species that reside in enriched waters.

Groundwater discharge into estuaries and the coastal ocean is an important mechanism for the transport of dissolved chemicals into coastal waters. Because many dissolved chemicals are present in groundwater in concentrations that are orders of magnitude higher than typical river concentrations, groundwater-borne nutrients and pollutants can have a substantial impact on the chemistry and biology of estuaries and the coastal ocean.

It has been suggested that terrestrial organic matter transported by rivers in general might be enriched in ^{14}C (Ludwig et al. 1996). Measurements of natural ^{14}C and ^{13}C data from a number of rivers indicate that they are variable sources of both old (^{14}C -depleted) and young (^{14}C -enriched) terrestrial DOC (Raymond & Bauer 2001, Bauer et al. 2002, Raymond et al. 2004). However, the results obtained here are more enriched than the few available estuarine measurements of ^{14}C . The methodology used in this study was standard for analyses of this type carried out in 2005, and prior and subsequent analyses of other otolith material (non jack mackerel) have not produced elevated levels of ^{14}C . A cross-check of all procedures from the time of receipt of the jack mackerel otoliths to the micro-milling laboratory, including otolith preparation, carbonate sampling, graphite conversion, and AMS measurement has been conducted, including the processing of the resin surrounding the jack mackerel otoliths, leading us to accept that these values are valid for the three individuals.

At best the results here suggest that these individuals are from stocks of *T. s. murphyi* that have been influenced by significantly enriched $\Delta^{14}\text{C}$. Without data of $\Delta^{14}\text{C}$ values from cores of known coastal stocks, prey types, New Zealand and South American estuaries and coastal waters, and evidence of juvenile behaviour, prey types and residence within waters elevated in $\Delta^{14}\text{C}$, along with reproduction of significantly enriched $\Delta^{14}\text{C}$ within cores, how these enriched levels occurred is nothing more than supposition. Given the indicated age of these individuals from growth zone counts, the documented first occurrence of *T. s. murphyi* in New Zealand waters and the distribution of populations from South America to west of New Zealand (Elizarov et al. 1993), it is possible the source of enriched $\Delta^{14}\text{C}$ is associated with the inshore South American coast.

4.2.2 Stable Isotopes

4.2.3 Temperature and depth history

The stable oxygen isotope chemistry has provided information on the ambient environmental conditions experienced by individual fish of *T. s. murphyi* throughout their life history. The $\delta^{18}\text{O}$ indicate that these individuals undergo temporal shifts in their temperature (and depth) distribution and therefore potentially their range during their life. The $\delta^{18}\text{O}$ variations can be divided into two intervals: prior to about growth zone 7, $\delta^{18}\text{O}$ enriches (temperature decrease, migration to cooler waters and/or depth increase); and after about growth zone 7, $\delta^{18}\text{O}$ is relatively constant (temperature and depth remain relatively constant) (Figures 19 and 20).

Temperatures estimated from *T. s. murphyi* core samples are consistent with near surface and sea surface temperatures (SST) for subtropical waters extending from offshore northern New Zealand across the Pacific (Figure 22) to offshore South America (e.g., Schweitzer 2001). This is consistent with the distribution of populations from South America to west of New Zealand (Elizarov et al. 1993) within subtropical water masses, but probably too consistently warm for the Snares region despite the influence of the STF (see section 1.2.2). This is consistent with the documented first occurrence of *T. s. murphyi* in New Zealand waters significantly after the estimated birth year of these individuals. However, the subsequent decrease in temperature is consistent with the trawl information for these individuals (caught in less than 400 m) and the few measured temperatures from the Snares region (see Figure 2). The temperature (and therefore potentially depth) distribution determined from isotopes is a measure of the main residence area while otolith carbonate is being laid

down; this does not preclude, for instance, short-term migrations into other water masses to forage or spawn.

4.2.4 Diet, metabolism, and dissolved inorganic carbon

From the stable carbon isotope chemistry it is possible to draw conclusions about variations in diet/metabolism and the role of DIC of seawater during the life history of the individual fish in this study. Approximately 30% of carbon is metabolically derived (Kalish 1991) with the remainder influenced by DIC in sea water (Schwarcz et al. 1998). The $\delta^{13}\text{C}$ changes recorded by the otoliths also fall into two intervals: a period of rapid enrichment prior about to growth zone 7, and a period of relatively constant $\delta^{13}\text{C}$ after about growth zone 7 (see Figure 19).

The recorded values and the patterns of $\delta^{13}\text{C}$ with increasing age are consistent with that seen in other studies (e.g. Schwarcz et al. 1998, Begg & Weidman 2001) The initial rapid enrichment in juvenile/young adult fish is considered to result from both an increase in the trophic level of the fish with age, probably concomitant with a shift in diet to higher trophic levels (Schwarcz et al. 1998, Begg & Weidman 2001). Subsequently, metabolic rate (and metabolic contribution) would be expected to decrease with age (Schwarcz et al. 1998). Species that display small departures from $\delta^{13}\text{C}$ equilibrium have low metabolic rates, and live in cold, deep waters. At the other end of the spectrum are the fast growing, highly active, homeothermic tunas and young fish that presumably have a higher metabolic rate, which also display a tendency to be more depleted in $\delta^{13}\text{C}$ (Kalish 1991). Hence both a shift in diet to higher trophic levels, and reduction in metabolism with age, are responsible for the increase in otolith $\delta^{13}\text{C}$ until the age of maturity. At maturity, most otoliths reach a maximum or asymptotic $\delta^{13}\text{C}$ value, after which $\delta^{13}\text{C}$ changes little or decreases slightly (Schwarcz et al. 1998).

The rapid enrichment of $\delta^{13}\text{C}$ from core values to growth zones 6–7, 6, and 4–5 in the three individuals of *T. s. murphyi* (see Figure 19) is therefore attributed to a change in diet and metabolic rate from the juvenile to the adult fish, potentially associated with migration with age. With no available information on prey, a change in diet from juvenile to adult cannot be unequivocally confirmed. The major change in gradient of the $\delta^{13}\text{C}$ curve is close to growth zones 5–7, hence it can be inferred that maturity is reached at this stage. At this time a relatively constant temperature/depth habitat has also been attained (see above). Assuming that zone formation is annual, then *T. s. murphyi* mature at age 5–7 years. While the reproductive biology is not well understood for this species this is consistent with suggested rapid initial growth slowing at an estimated 6–7 years. There is variation between the individual otoliths (especially from JMM1) but given the small sample size and limited information on otolith provenance, little can be stated about the cause of variation at this stage.

4.2.5 Bomb radiocarbon conclusions

Validation of fish age estimates (from otoliths annuli counts) using the bomb radiocarbon relies on being able to detect the increase in ^{14}C concentration that is found in otoliths growing during the years when nuclear weapons-derived ^{14}C was first appearing in the surface ocean waters (1955–1963). From radiocarbon analyses, the ages of three individuals of Murphy's mackerel could not be successfully validated as the Jack mackerel otoliths tested had significantly enriched $\Delta^{14}\text{C}$ values within their cores. To understand this, information is required on the origin, migration, juvenile behaviour, and prey types. Most importantly we need to know $\Delta^{14}\text{C}$ values from cores of known mackerel coastal stocks, from prey types, and from New Zealand and South American estuaries and coastal waters. We also need to know residence within waters elevated in $\Delta^{14}\text{C}$.

Some valuable insights into the life histories of *T. s. murphyi* were obtained from the stable isotope analyses. Estimates of the temperatures/depths in which the adult fish reside are consistent with

information recorded by trawl data. However, when young, the individuals apparently resided in significantly warmer subtropical waters, at least prior to estimated age 7, probably outside of New Zealand waters and did not reside in or migrate into cooler Pacific or New Zealand waters until after this time. It is suggested that individuals also reached maturity at about this same time. It is desirable, however, that a better understanding of *T. s. murphyi* be obtained.

5 ACKNOWLEDGMENTS

This research was carried out by NIWA under contract to the Ministry of Fisheries (project JMA200301). We acknowledge the practical assistance and advice given to us by NIWA and GNS staff during this study. In particular, Rodger Sparks and Christine Prior from GNS Science provided valuable discussion on the elevated radiocarbon results and analysis of resin blanks. We thank NIWA staff Derek Kater for preparation of the otoliths, and Mike Stevenson and Ron Blackwell for reading the otoliths. We also thank Peter Horn (NIWA) for reviewing the report and Marianne Vignaux (MPI) for editorial comments.

6 REFERENCES

- Araya, M.; Cubillos, L.A.; Guzmán, M.; Peñailillo, J.; Sepúlveda, A. (2001). Evidence of a relationship between age and otolith weight in the Chilean jack mackerel *Trachurus symmetricus murphyi* (Nichols). *Fisheries Research* 51: 17–26.
- Baker, M.S. Jr.; Wilson, C.A. (2001). Use of bomb radiocarbon to validate otolith section ages of red snapper *Lutjanus campechanus* from the northern Gulf of Mexico. *Limnology and Oceanography* 46: 1819–1824.
- Bauer, J.E.; Druffel, E.R.M.; Wolgast, D.M.; Griffin, S. (2002). Temporal and regional variability in sources and cycling of DOC and POC in the northwest Atlantic continental shelf and slope. *Deep-Sea Research II* 49: 4387–4419.
- Beamish, R.J. (1979). Differences in the age of Pacific hake (*Merluccius productus*) using whole otoliths and section otoliths. *Journal of the Fisheries Research Board of Canada* 36: 141–151.
- Beamish, R.J.; McFarlane, G.A. (1983). The forgotten requirement for age validation in fisheries biology. *Transactions of the American Fisheries Society* 112: 735–743.
- Begg, G.A.; Weidman, C.R. (2001). Stable ^{13}C and ^{18}O isotopes in otoliths of haddock *Melanogrammus aeglefinus* from the northwest Atlantic Ocean. *Marine Ecology Progress Series* 216: 223–233.
- Campana, S.E. (1997). Use of radiocarbon from nuclear fallout as a dated marker in the otoliths of haddock *Melanogrammus aeglefinus*. *Marine Ecology Progress Series* 150: 49–56.
- Campana, S.E. (1999). Chemistry and composition of fish otoliths: pathways, mechanisms and applications. *Marine Ecology Progress Series* 188: 263–297.
- Campana, S.E. (2001). Accuracy, precision, and quality control in age determination, including a review of the use and abuse of age validation methods. *Journal of Fish Biology* 59: 197–242.
- Campana, S.E.; Gagne, J.A.; McLaren, J.W. (1995). Elemental fingerprinting of fish otoliths using ID-ICPMS. *Marine Ecology Progress Series* 122: 115–120.
- Campana, S.E.; Jones, C.M. (1997). Radiocarbon from nuclear testing applied to age validation of black drum, *Pogonias cromis*. *Fishery Bulletin* 96: 185–192.
- Campana, S.E.; Natanson, L.J.; Myklevoll, S. (2002). Bomb dating and age determination of large pelagic sharks. *Canadian Journal of Fisheries and Aquatic Science* 59: 450–455.
- Campana, S.E.; Thorrold, S.R. (2001). Otoliths, increments, and elements: keys to a comprehensive understanding of fish populations? *Canadian Journal of Fisheries and Aquatic Science* 58: 30–38.

- CANZ (1996). Undersea New Zealand (New Zealand Region Physiography). 1:4,000,000 (2nd ed.). *New Zealand Oceanographic Institute Chart, Miscellaneous Series 74*.
- Carrera, P.P.; Collantes, E.S. (1978). Determinacion de edad y crecimiento del jurel *Trachurus murphyi* Nichols, 1920. *Investigaciones Marinas* 6: 89–100.
- Chiswell, S.M. (1994). Acoustic doppler current profiler measurements over the Chatham Rise. *New Zealand Journal of Marine and Freshwater Research* 28: 167–178.
- Elizarov, A.A.; Grechina, A.S.; Botenev, B.N.; Kuzetsov, A.N. (1993). Peruvian jack mackerel, *Trachurus symmetricus*, in the open waters of the South Pacific. *Journal of Ichthyology* 33: 86–104.
- Gao, Y.; Schwarcz, H.P.; Brand, U.; Moksness, E. (2001). Seasonal stable isotope records of otoliths from ocean-pen reared and wild cod, *Gadus morhua*. *Environmental Biology of Fishes* 61: 445–453.
- Grossman, E.L.; Ku, T.L. (1986). Oxygen and carbon stable isotope fractionation in biogenic aragonite: temperature effects. *Chemical Geology* 59: 59–74.
- Hadfield, M.G.; Rickard, G.J.; Uddstrom, M.J. (2007). A hydrodynamic model of Chatham Rise, New Zealand. *New Zealand Journal of Marine & Freshwater Research* 41: 239–264.
- Horn, P.L. (1993). Growth, age structure, and productivity of jack mackerels (*Trachurus* spp.) in New Zealand waters. *New Zealand Journal of Marine and Freshwater Research* 27: 145–155.
- Kaiser, C.E. (1973). Age and growth of horse mackerel *Trachurus murphyi* off Chile. *Transactions of the American Fisheries Society* 102: 591–595.
- Kalish, J.M. (1991). ^{13}C and ^{18}O isotopic disequilibria in fish otoliths: metabolic and kinetic effects. *Marine Ecology Progress Series* 75: 191–203.
- Kalish, J.M. (1993). Pre- and post-bomb radiocarbon in fish otoliths. *Earth and Planetary Science Letters* 114: 549–554.
- Kalish, J.M. (1995). Application of the bomb radiocarbon chronometer to the validation of redbfish *Centroberyx affinis* age. *Canadian Journal of Fisheries and Aquatic Sciences* 52: 1399–1405.
- Kalish, J.M.; Johnston, J.M.; Gunn, J.S.; Clear, N.P. (1996). Use of the bomb radiocarbon chronometer to determine age of southern bluefin tuna *Thunnus maccoyii*. *Marine Ecology Progress Series* 143: 1–8.
- Kalish, J.M.; Johnston, J.M.; Smith, D.C.; Morison, A.K.; Robertson, S.G. (1997). Use of the bomb radiocarbon chronometer for age validation in the blue grenadier *Macruronus novaezelandiae*. *Marine Biology* 128: 557–563.
- Karlen, I.; Olsson, I.U.; Kallberg, P.; Kilicci, S. (1964). Absolute determination of the activity of two ^{14}C dating standards. *Arkiv For Geofysik Band 4* 22: 465–471.
- Kawahara, S.; Uozumi, Y.; Yamada, H. (1988). First record of a carangid fish *Trachurus murphyi* from New Zealand. *Japanese Journal of Ichthyology* 35: 212–214.
- Kim, S.T.; O'Neil, J.R. (1997). Equilibrium and nonequilibrium oxygen isotope effects in synthetic carbonates. *Geochimica Cosmochimica Acta* 61: 3461–3475.
- Kochkin, P.N. (1980). A technique for preparation of thin sections of mineralized structures of fishes and mammals (In Russian). *Zoologicheskii Zhurnal* 59: 289–293.
- Kochkin, P.N. (1986). Analysis of age sensitive structures and linear growth in the pike glassfish, *Champscephalus gunnari* (Channichthyidae). *Journal of Ichthyology* 25: 110–119.
- Kochkin, P.N. (1994). Age determination and estimate of growth rate for the Peruvian jack mackerel, *Trachurus symmetricus murphyi*. *Journal of Ichthyology* 34: 39–50.
- Kroopnick, P. (1985). The distribution of C-13 of TCO_2 in the world oceans. *Deep Sea Research* 32: 57–84.
- Ludwig, W.; Probst, J.-L.; Kempe, S. (1996). Predicting the oceanic input of organic carbon by continental erosion. *Global Biogeochemical Cycles* 10: 23–42.
- Morison, A.K.; Kalish, J.M.; Green, C.P.; Johnston, J.M. (1999). Estimation of age and growth of orange roughy, black oreo and smooth oreo, and natural mortality of black and smooth oreo. Final report to the New Zealand Ministry of Fisheries (99/45). Marine and Freshwater

- Resources Institute, Queenscliff, Victoria, Australia. 67 p. (Unpublished report held by Ministry of Fisheries, Wellington.)
- Neil, H.L.; Carter, L.; Morris, M.Y. (2004). Thermal isolation of Campbell Plateau, New Zealand, by the Antarctic Circumpolar Current over the past 130 kyr, *Paleoceanography*, 19, PA4008, doi:10.1029/2003PA000975.
- Northcote, T.G.; Hendy, C.H.; Nelson, C.S.; J.A.T., Boubee (1992). Tests for migratory history of the New Zealand common smelt (*Retropinna retropinna*) using otolith isotopic composition. *Ecology of Freshwater Fish 1*: 61–72.
- Paul, L.J.; Francis, M.P. (2002). Estimates of age, and mortality parameters of sea perch (*Helicolenus percooides*) off the east coast of the South Island, New Zealand. Final Research Report for Ministry of Fisheries Research Project SPE2000/01, Objective 1 and 2. 55p (Unpublished report held at Ministry of Fisheries, Wellington.)
- Paul, L.J.; Horn, P.L.; Francis, M.P. (2000). Development of an ageing methodology, and first estimates of growth parameters and natural mortality for rubyfish (*Plagiogeneion rubiginosum*) off the east coast of the North Island (QMA 2). *New Zealand Fisheries Assessment Report 2000/22*. 28 p.
- Radtke, R.L.; Williams, D.F.; Hurley, P.C.F. (1987). The stable isotope composition of bluefin tuna (*Thunnus thynnus*) otoliths: evidence for physiological regulation. *Comparative Biochemistry and Physiology 87A*: 797–801.
- Raymond, P.A.; Bauer, J.E. (2001). Riverine export of aged terrestrial organic matter to the North Atlantic Ocean. *Nature 409*: 497–500.
- Raymond, P.A.; Bauer, J.E.; Caraco, N.F.; Cole, J.J.; Longworth, B.; Petsch, S.T. (2004). Controls on the variability of organic matter and dissolved inorganic carbon ages in northeast US rivers. *Marine Chemistry 92*: 353–366.
- Reynolds, R.W.; Rayner, N.A.; Smith, T.M.; Stokes, D.C.; Wang, W. (2002). An Improved In Situ and Satellite SST Analysis for Climate. *Journal of Climate 15*: 1609–1625.
- Roelke, L.A.; Cifuentes, L.A. (1997). Use of stable isotopes to assess groups of king mackerel, *Scomberomorus cavalla*, in the Gulf of Mexico and southeastern Florida. *Fishery Bulletin 95*: 540–551.
- Romanek, C.S.; Grossman, E.L.; Morse, J.W. (1992). Carbon isotope fractionation in synthetic aragonite and calcite: effects of temperature and precipitation rate. *Geochimica Cosmochimica Acta 56*: 419–430.
- Savin, S.M.; Abel, L.; Barrera, E.; Hodell, D.; Keller, G. (1985). The evolution of Miocene surface and near-surface marine temperatures: oxygen isotopic evidence. In: *The Miocene Ocean: Paleoceanography and Biogeography*, ed J.P. Kennett, *Memoirs Geological Society of America*, 163, 49–82.
- Schmidt, G.A.; Bigg, G.R.; Rohling, E.J. (1999). Global seawater oxygen-18 database, <http://data.giss.nasa.gov/o18data>
- Schwarcz, H.P.; Gao, Y.; Campana, S.; Browne, D.; Knyf, M.; Brand, U. (1998). Stable carbon isotope variations in otoliths of Atlantic cod (*Gadus mohua*). *Canadian Journal of Fisheries and Aquatic Science 55*: 1798–1806.
- Schweitzer, P.N. (2001). Modern Average Global Sea-Surface Temperature U.S. Geological Survey Digital Data Series DDS-10, <http://pubs.usgs.gov/dds/dds10/magsst>.
- Shcherbich, L.V. (1992). Methods of age determination in the horse mackerel, *Trachurus capensis*, by scales and otoliths. *Journal of Ichthyology 32*: 46–59.
- Stanton, B.R.; Ridgway, N.M. (1988). An oceanographic survey of the subtropical convergence zone in the Tasman Sea. *New Zealand Journal of Marine and Freshwater Research 22*: 583–593.
- Stuiver, M.; Polach, H.A. (1977). Discussion: reporting of ¹⁴C data. *Radiocarbon 19*: 355–363.
- Taylor, P.R. (2002). Stock structure and population biology of the Peruvian jack mackerel, *Trachurus symmetricus murphyi*. *New Zealand Fisheries Assessment Report 2002/21*. 78 p.
- Taylor, P.R.; Manning, M.J.; Marriot, P.M. (2002). Age and growth estimation of Murphy's mackerel, *Trachurus symmetricus murphyi*. Final Research Report to the Ministry of

- Fisheries for Project JMA2002/02. (Unpublished report held by Ministry for Primary Industries, Wellington). 62 p
- Thorrold, S.R.; Campana, S.E.; Jones, C.M.; Swart, P.K. (1997). Factors determining ^{13}C and ^{18}O fractionation in aragonitic otoliths of marine fish. *Geochimica Cosmochimica Acta* 61: 2909–2919.
- Uddstrom, M.J. ; Oien, N.A. (1999). On the use of high-resolution satellite data to describe the spatial and temporal variability of sea surface temperatures in the New Zealand region. *Journal of Geophysical Research* 104: 20729–20751.
- Wellington, G.M.; Dunbar, R.B. ; Merlen, G. (1996). Calibration of stable oxygen isotope signatures in Galápagos corals. *Paleoceanography* 11: 467–480.
- Wysokinski, A. (1985). Horse mackerel age determination using otoliths. Collection of scientific papers. *International Commission for the Southeast Atlantic Fisheries* 12: 199–203.

Table 1: Murphy's mackerel otoliths used in the whole otolith corrugation/ring counts, marginal state analysis, and thin section narrow-zone readings. The New Zealand otoliths were collected by the stock monitoring programme (SMP), and of the 480, 30 were from JMA 1 and the remainder from JMA 7.

Month/year	Area	Fishstock	Total
February 05	CHA	JMA 7	51
March 05	CHA	JMA 7	50
April 05	CHA	JMA 7	50
May 05	CEE	JMA 1	9
June 05	CHA	JMA 7	50
July 05			0
August 05	CHA	JMA 7	42
September 05	TBGB, WCSI	JMA 7	51
October 05	WCNI, WCSI, JMA 1	JMA 7, JMA 1	18
November 05	WCSI, JMA 1	JMA 7, JMA 1	55
December 05	CHA, WCSI	JMA 7	52
January 06	CHA, WCSI	JMA 7	53
January 98	Chile		6
September 98	Chile		1
Total			487

Table 2: Reported values of carbon and oxygen isotopes and predicted temperature for jack mackerel *Trachurus symmetricus murphyi*. Data blanks are a result of low sample voltage or balance and are consequently not reported.

^a where salinity = 34.7‰

^b where salinity = 34.8‰

^c where ambient $\delta^{18}\text{O}$ seawater = 0.3, east coast New Zealand

^d where ambient $\delta^{18}\text{O}$ seawater = 0.4, Galapagos Islands

Trip	Station	Fish No:	Sample	Growth Zone Count	Estimated age mid-point	Carbon $\delta^{13}\text{C}$	Oxygen $\delta^{18}\text{O}$	Temperature (°C) ^a	Temperature (°C) ^b	Temperature (°C) ^c	Temperature (°C) ^d
AEX8902	98	JMM1	0	21–24	22.5						
			1	19–20	19.5						
			2	17–18	17.5						
			3	15–16	15.5						
			4	13–14	13.5						
			5	12	12	-3.80	1.46	11.4	11.7	12.4	12.9
			6	10–11	10.5	-3.80	1.46	11.4	11.7	12.4	12.9
			7	9	9	-3.10	1.59	10.8	11.1	11.8	12.3
			8	8	8	-2.42	1.58	10.8	11.2	11.8	12.3
			9	7	7	-2.07	1.30	12.2	12.5	13.2	13.6
			10	6	6.5	-1.93	1.39	11.7	12.1	12.7	13.2
			11	6	6	-2.51	1.24	12.5	12.8	13.5	13.9
			12	5	5.5	-3.42	1.11	13.1	13.5	14.1	14.6
			13	5	5	-3.84	0.79	14.7	15.0	15.6	16.1
			14	4	4	-4.46	0.55	15.8	16.2	16.8	17.3
			15	3	3.5	-4.81	0.70	15.1	15.4	16.1	16.5
			16	3	3	-5.26	0.65	15.4	15.7	16.3	16.8
			17	2	2	-4.97	0.46	16.2	16.6	17.2	17.7
			18	1	1	-4.47	0.42	16.5	16.8	17.4	17.9
			19	0	0.5	-4.18	0.56	15.8	16.1	16.7	17.2
20	0	0	-4.47	0.13	17.9	18.2	18.8	19.3			

Trip	Station	Fish No:	Sample	Growth Zone Count	Estimated age mid-point	Carbon $\delta^{13}\text{C}$	Oxygen $\delta^{18}\text{O}$	Temperature ($^{\circ}\text{C}$) ^a	Temperature ($^{\circ}\text{C}$) ^b	Temperature ($^{\circ}\text{C}$) ^c	Temperature ($^{\circ}\text{C}$) ^d
AEX8902	98	JMM2	0	22–23	22.5						
			1	21	21						
			2	20	20	-3.31	1.70	10.2	10.6	11.2	11.7
			3	19	19	-3.18	1.83	9.6	10.0	10.6	11.1
			4	18	18	-3.17	1.79	9.8	10.1	10.8	11.3
			5	16–17	16.5	-3.10	1.77	9.9	10.3	10.9	11.4
			6	15	15	-2.95	1.57	10.9	11.2	11.9	12.3
			7	13–14	13.5	-3.30	1.69	10.3	10.6	11.3	11.7
			8	12	12	-3.38	1.72	10.2	10.5	11.1	11.6
			9	11	11	-1.91	0.60	15.6	15.9	16.6	17.0
			10	9–10	9.5	-3.35	1.63	10.6	10.9	11.5	12.0
			11	8	8	-3.31	1.64	10.5	10.9	11.5	12.0
			12	7	7.5	-3.14	1.60	10.7	11.1	11.7	12.2
			13	7	7	-3.09	1.56	10.9	11.3	11.9	12.4
			14	6	6.5	-3.04	1.41	11.7	12.0	12.6	13.1
			15	6	6	-2.54	1.31	12.1	12.5	13.1	13.6
			16	5	5.5	-2.68	1.26	12.4	12.7	13.4	13.8
			17	5	5	-3.09	0.76	14.8	15.1	15.8	16.2
			18	4	4	-3.20	0.58	15.7	16.0	16.7	17.1
			19	3	3.5	-3.40	0.87	14.3	14.6	15.2	15.7
			20	3	3	-3.61	0.56	15.8	16.1	16.8	17.2
			21	2	2.5	-3.36	0.51	16.0	16.4	17.0	17.5
			22	2	2	-3.71	0.58	15.7	16.0	16.7	17.1
			23	1	1.5	-4.28	0.56	15.8	16.1	16.7	17.2
			24	1	1	-4.32	0.55	15.8	16.1	16.8	17.3
			25	0	0.75	-4.04	0.32	17.0	17.3	17.9	18.4
			26	0	0.5	-3.98	0.19	17.6	17.9	18.5	19.0
			27	0	0.25						
			28	0	0						

Trip	Station	Fish No:	Sample	Growth Zone Count	Estimated age mid-point	Carbon $\delta^{13}\text{C}$	Oxygen $\delta^{18}\text{O}$	Temperature (°C) ^a	Temperature (°C) ^b	Temperature (°C) ^c	Temperature (°C) ^d
AEX8902	98	JMM3	0	25	25	-3.22	1.60	10.7	11.1	11.7	12.2
			1	23–24	23.5	-3.22	1.60	10.7	11.1	11.7	12.2
			2	21–22	21.5	-3.29	1.57	10.9	11.2	11.8	12.3
			3	19–20	19.5	-3.29	1.57	10.9	11.2	11.8	12.3
			4	17–18	17.5	-3.13	1.70	10.3	10.6	11.2	11.7
			5	16	16	-3.02	1.66	10.5	10.8	11.4	11.9
			6	15	15	-2.90	1.60	10.7	11.1	11.7	12.2
			7	13–14	13.5	-2.88	1.54	11.0	11.4	12.0	12.5
			8	12	12	-2.94	1.54	11.0	11.3	12.0	12.5
			9	11	11	-2.90	1.47	11.3	11.7	12.3	12.8
			10	9–10	9.5	-2.91	1.36	11.9	12.2	12.9	13.4
			11	8	8	-2.83	1.28	12.3	12.6	13.2	13.7
			12	7	7	-2.73	1.19	12.7	13.1	13.7	14.2
			13	6	6	-2.62	1.11	13.1	13.4	14.1	14.6
			14	5	5	-2.64	0.86	14.3	14.7	15.3	15.8
			15	4	4.5	-2.39	1.06	13.4	13.7	14.3	14.8
			16	4	4	-2.60	0.91	14.1	14.4	15.0	15.5
			17	3	3.5	-2.95	0.77	14.7	15.1	15.7	16.2
			18	3	3	-3.34	0.58	15.7	16.0	16.7	17.2
			19	2	2.66	-3.72	0.42	16.5	16.8	17.4	17.9
			20	2	2.33	-3.65	0.67	15.2	15.6	16.2	16.7
			21	2	2	-3.79	0.98	13.7	14.1	14.7	15.2
			22	1	1.5	-4.07	0.63	15.4	15.8	16.4	16.9
			23	1	1						
			24	0	0.66	-4.53	0.35	16.8	17.1	17.8	18.2
			25	0	0.33	-4.77	0.17	17.7	18.0	18.7	19.1
			26	0	0	-5.05	0.11	18.0	18.3	18.9	19.4

Table 3: Radiocarbon data for jack mackerel *Trachurus symmetricus murphyi*.

Trip	Station	Fish No:	Catch Date	Growth Zone Count	Birth Year	Sample	Estimated age range	Estimated year range	$\delta^{13}\text{C}$	$\Delta^{14}\text{C}$ □
AEX8902	98	JMM1	10-Nov-89	25	1964	core	0–1	1964–65	-4.86	$513.3 \pm 5.4 \text{ ‰}$
AEX8902	98	JMM2	10-Nov-89	23	1966	core	0–1	1966–67	-4.5	$491.5 \pm 5.9 \text{ ‰}$
AEX8902	98	JMM2				outer	5–23	1971–89	-4	$110.57 \pm 0.4 \text{ ‰}$
AEX8902	98	JMM3	10-Nov-89	25	1964	core	0–1	1964–65	-5	$270.8 \pm 5.2 \text{ ‰}$

Modern Currents

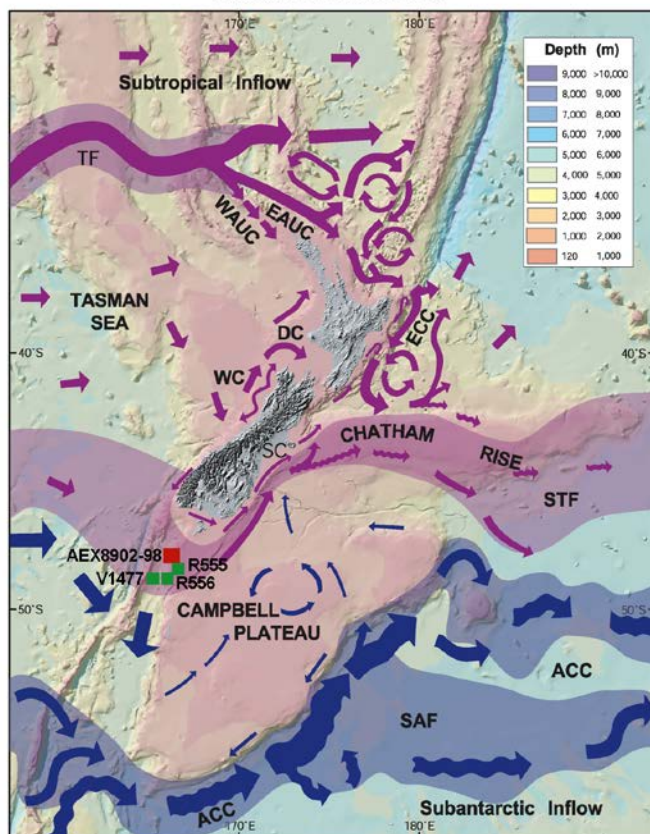


Figure 1: Bathymetry and representation of the currents around New Zealand at the present day, modified from Neil et al. (2004). Bathymetry after CANZ (1996). Also plotted are positions of Snares CTD profiles (green) and trawl (red) where jack mackerel otoliths used in bomb-radiocarbon analyses were sampled. (STW = Subtropical Water, SAW = Subantarctic Surface Water, CSW = Circumpolar Surface Water, STF = Subtropical Front, SAF = Subantarctic Front, SF = Southland Front, MS = Mernoo Saddle), TF = Tasman Front, MS = Mernoo Saddle, EAUC = East Auckland Current, WAUC = West Auckland Current, ACC = Antarctic Circumpolar Current, ECC = East Cape Current, WC = Westland Current, DC = D’).

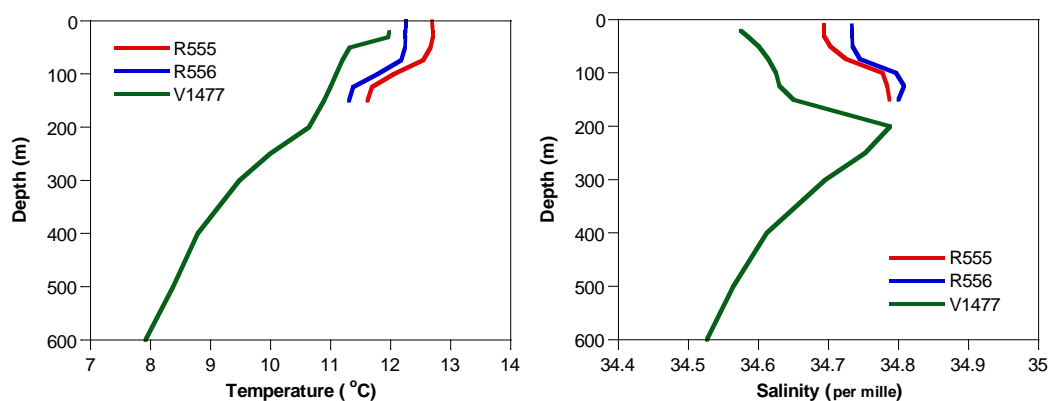


Figure 2: Hydrographic (temperature and salinity) profiles from the Snares region of New Zealand. Location of profiles illustrated in Figure 1.

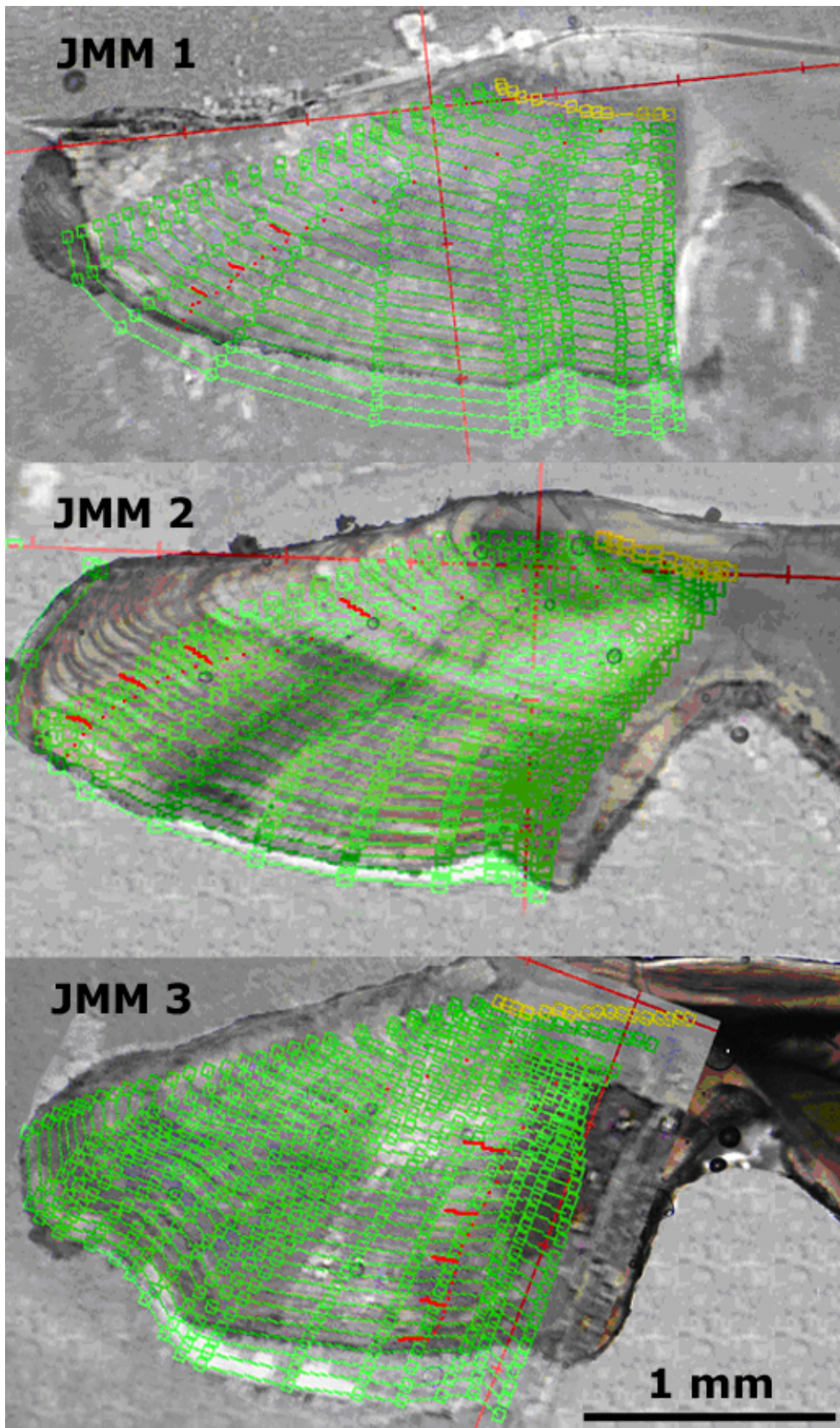


Figure 3: Images of jack mackerel *Trachurus symmetricus murphyi* thin sections overlain by images of the milled sister otoliths, the green scanlines show the path followed by the milling tip during each sample extraction, e.g. JMM 3 had 26 samples extracted. The pairs of images do not overlay exactly as the sister otoliths are not exact mirror copies of each other. These images are used as a tool to correlate the zones contained in each sample extraction. Red dots and dashes mark individual zones.

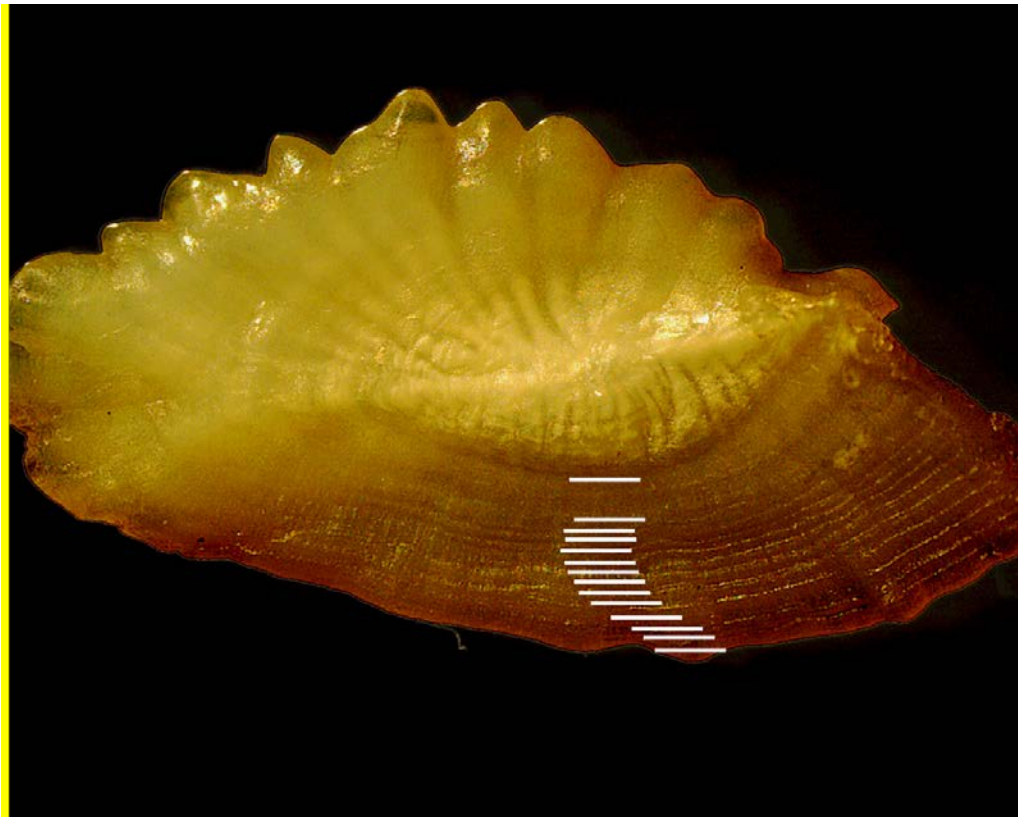


Figure 4: Photomicrograph of distal surface of a whole left sagitta otolith of Murphy's mackerel (trip code 20056510, fish No. 8, slide 35b, 49 cm FL, male). Top – corrugations viewed through reflected light. Bottom – rings viewed through transmitted light. Next page - The thin section growth zones using the narrow-zone method are marked, as are the approximate positions of the corrugations.

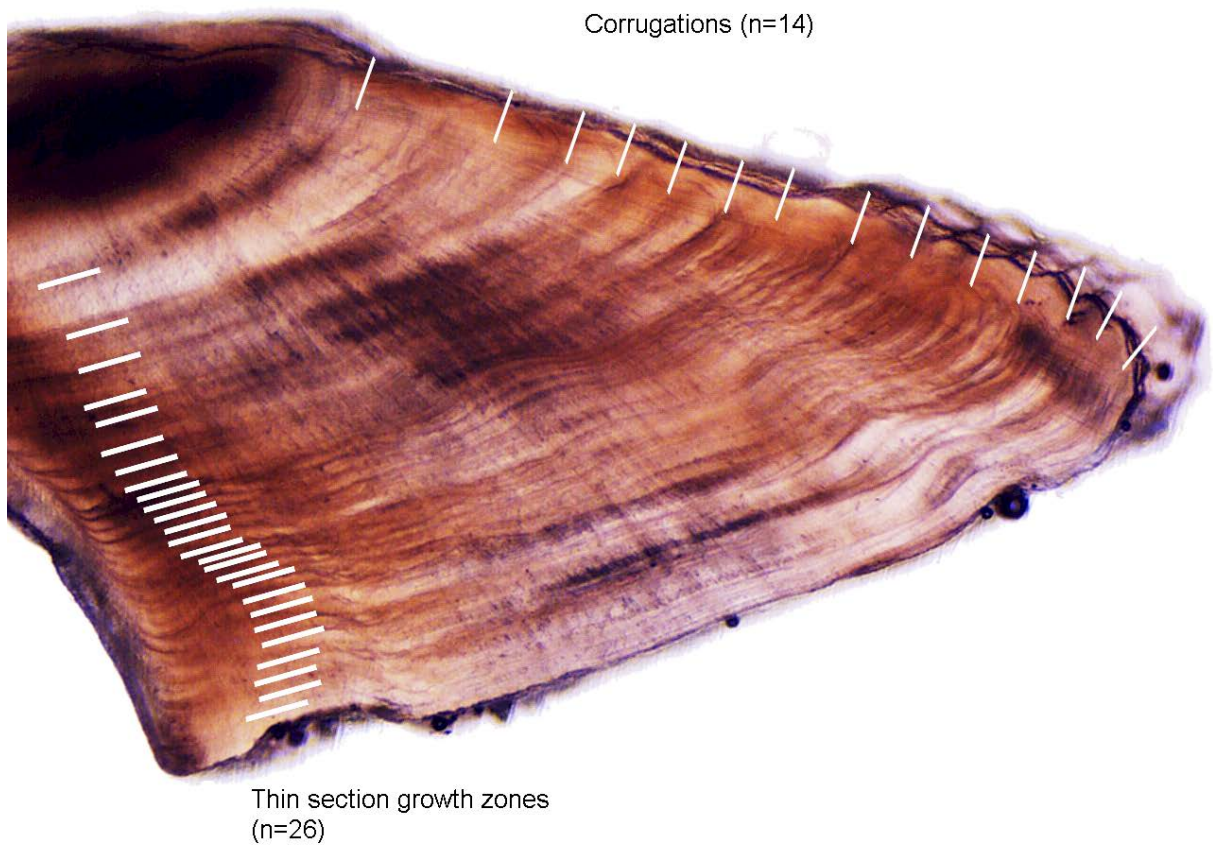


Figure 4 – continued

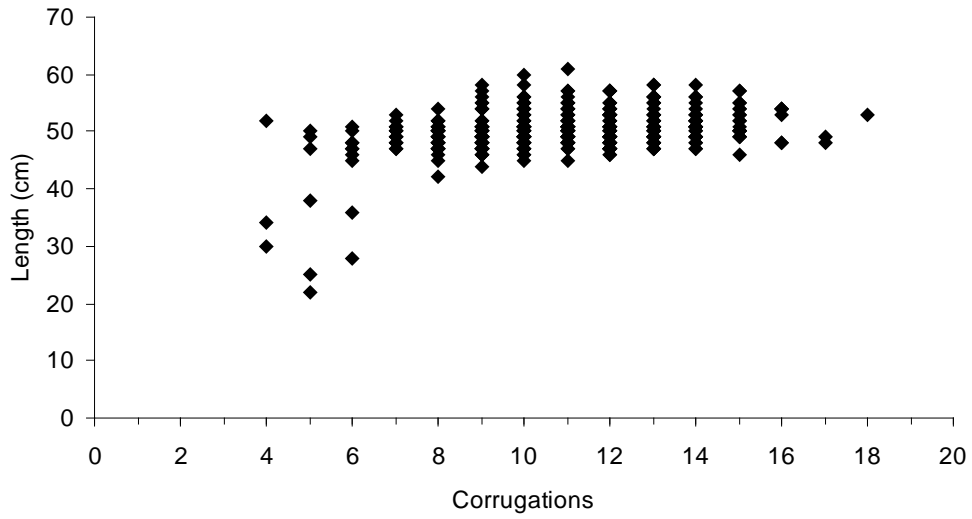


Figure 5: Fork length versus corrugation counts from whole otoliths. N= 462.

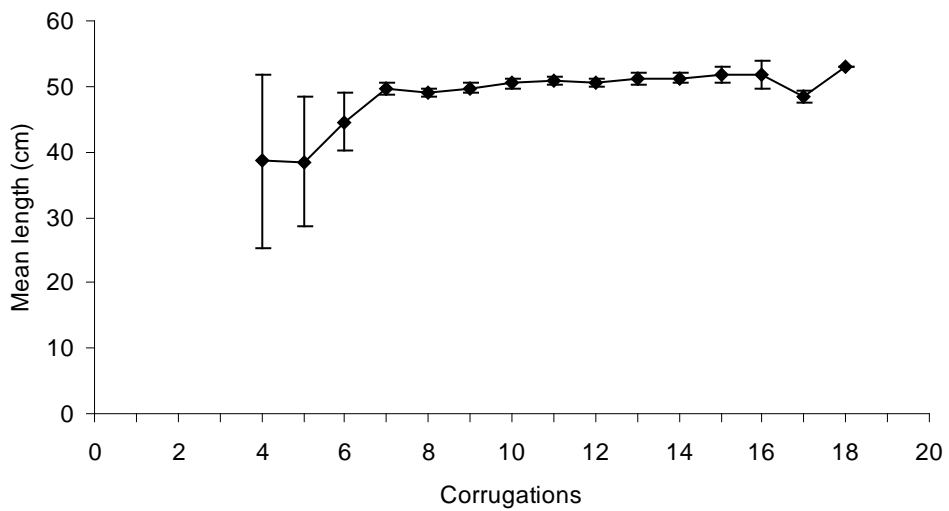


Figure 6: Mean fork length versus corrugation counts from whole otoliths. N= 462. Error bars are 95% confidence intervals.

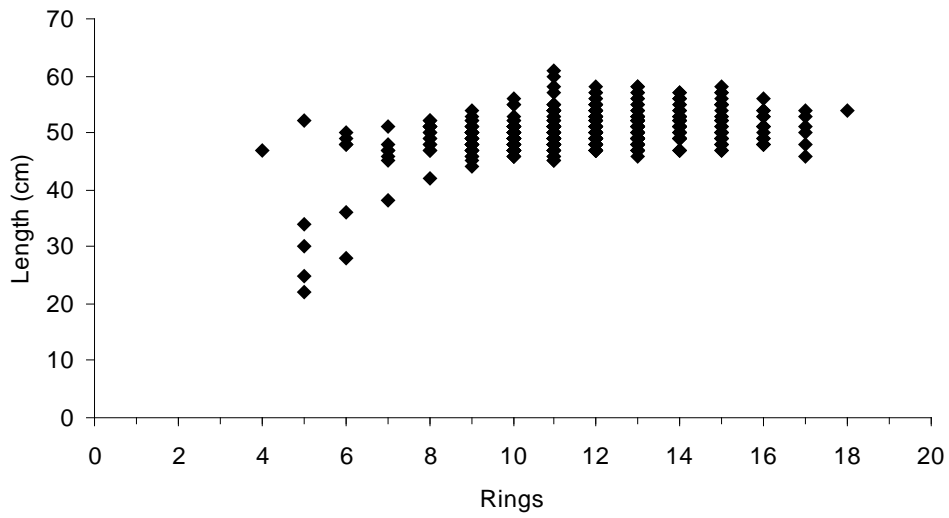


Figure 7: Fork length versus ring counts from whole otoliths. N= 463.

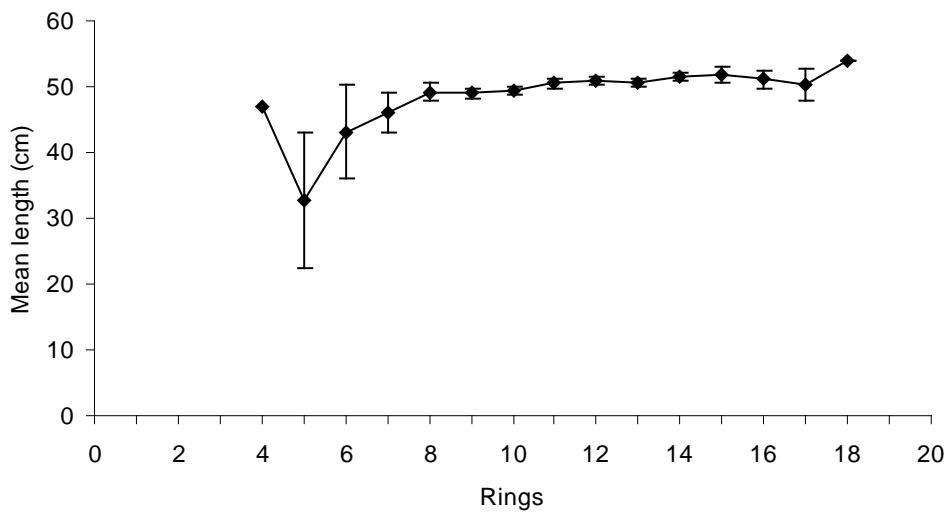


Figure 8: Mean fork length versus ring counts from whole otoliths. N= 463. Error bars are 95% confidence intervals.

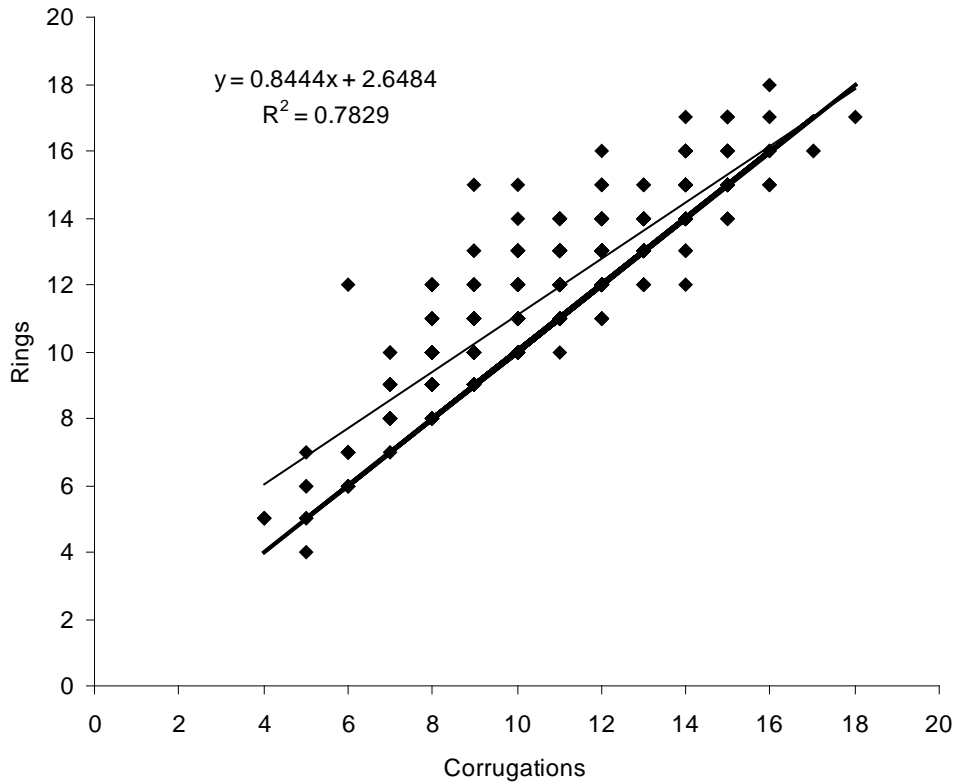


Figure 9: Ring count plotted against the corrugation count from whole otoliths. N = 462. The lighter line is the linear regression fit to the scatterplot and the regression equation for this fit is shown. The dark line indicates where a 1 to 1 relationship would lie.

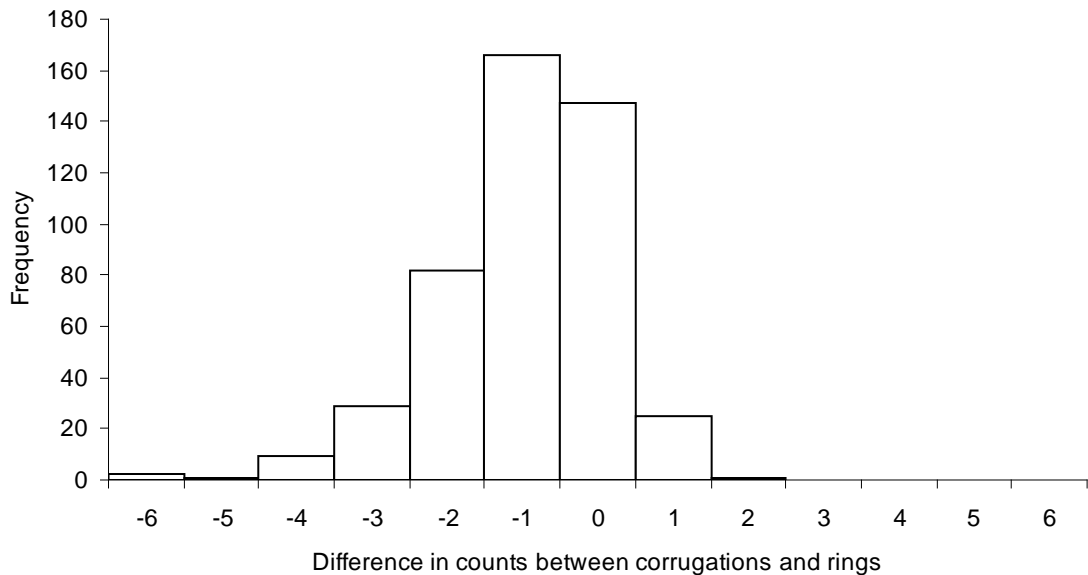


Figure 10: Difference between corrugation and ring counts from whole otoliths. N=462. On average there were more rings counted than corrugations (see Figure 9).

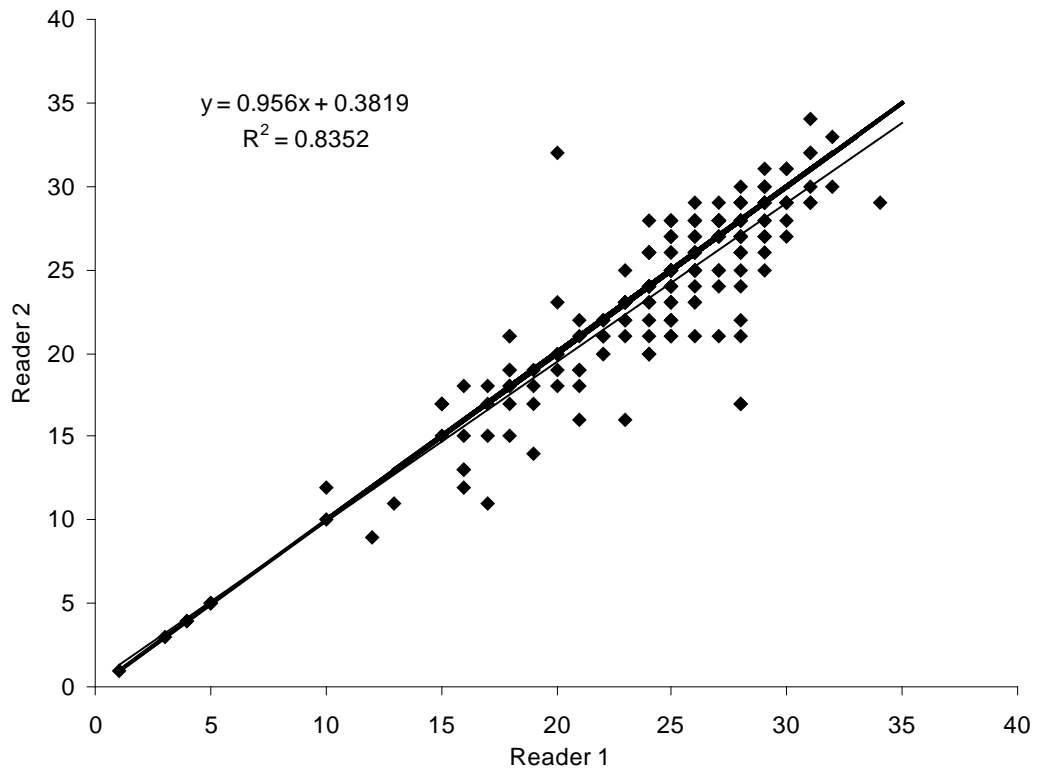


Figure 11: Comparison of reader 1 and reader 2 thin section zone counts. N = 190. The lighter line is the linear regression fit to the scatter plot and the regression equation for this fit is shown. The dark line indicates where a 1 to 1 relationship would lie.

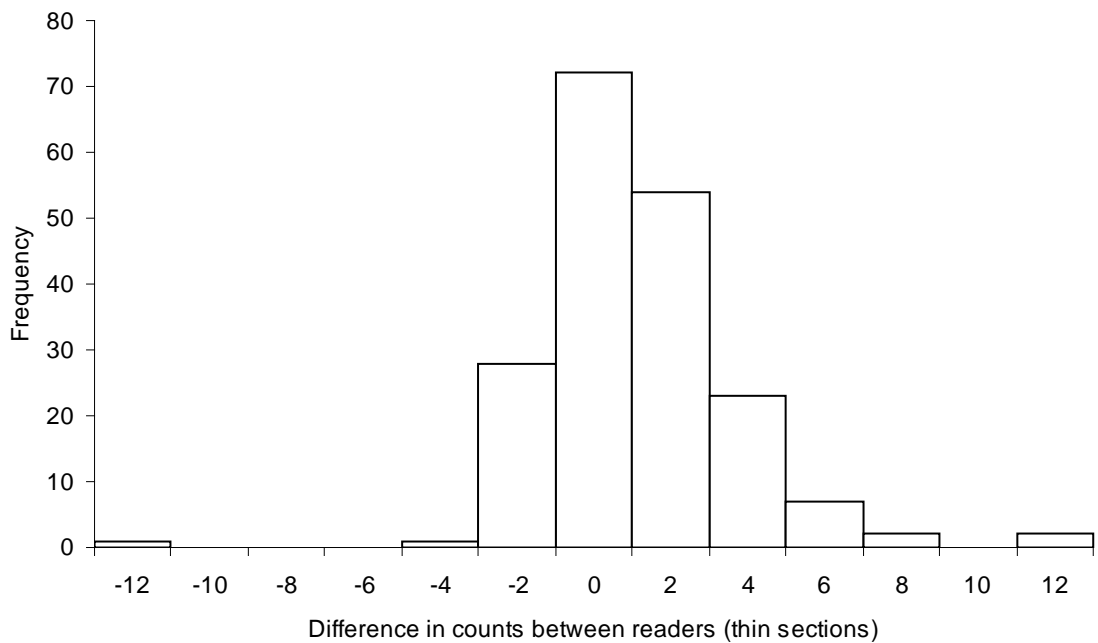


Figure 12: Difference between reader 1 and reader 2 of the zones counts from thin sections. N=190.

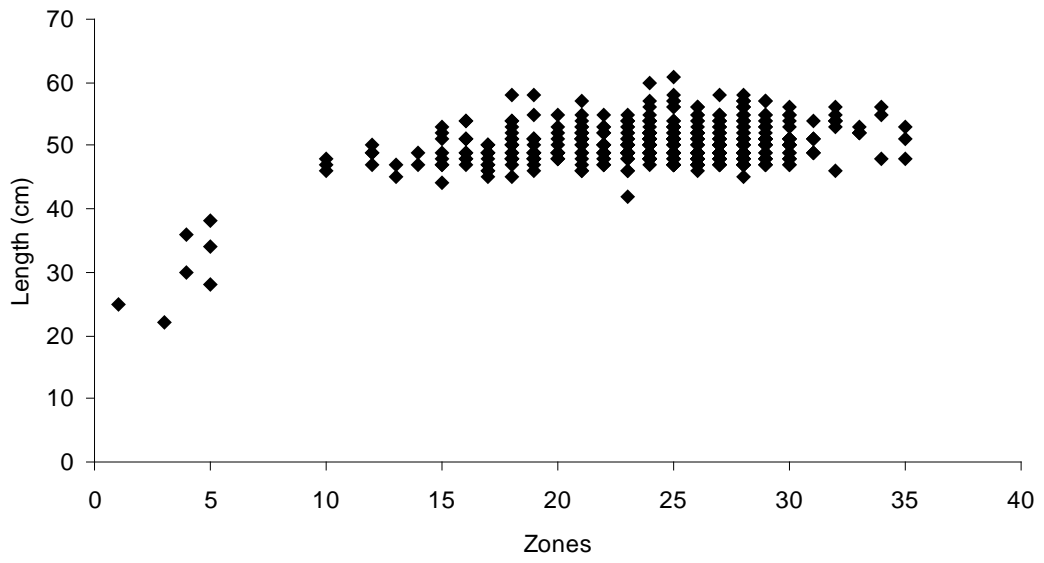


Figure 13: Fork length versus thin section zones for agreed readings. N= 469.

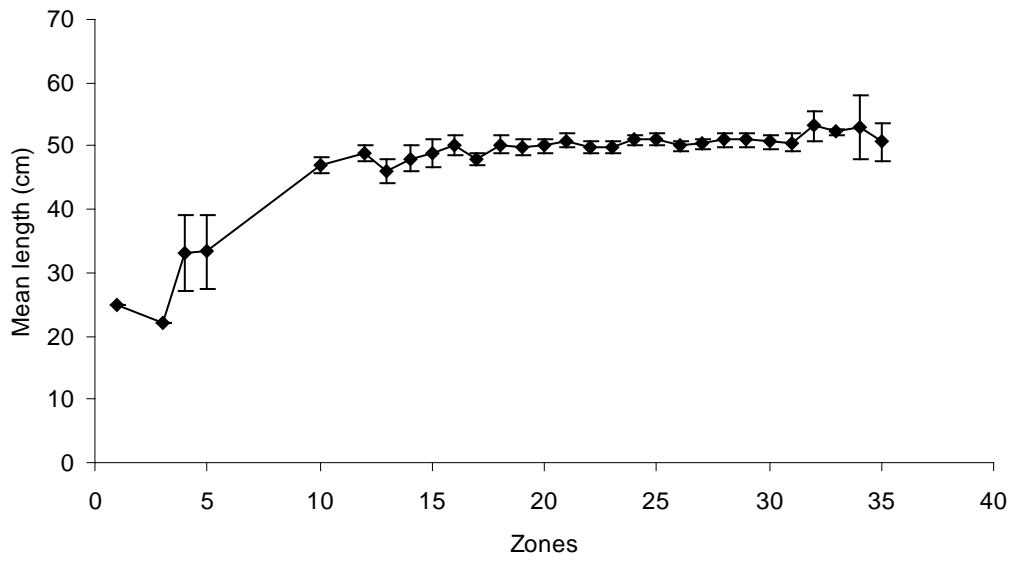


Figure 14: Mean fork length versus thin section zones for agreed readings. N= 469. Error bars are 95% confidence intervals.

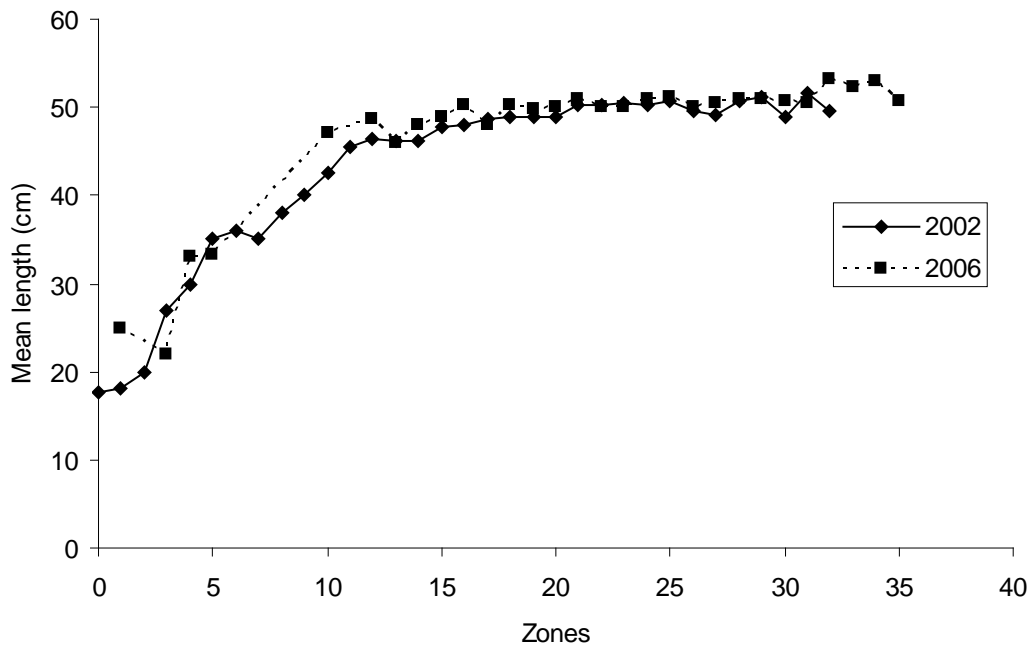


Figure 15: Comparison of mean length at zone count from thin sections in 2002 (Taylor et al. 2002), and this study (2006).

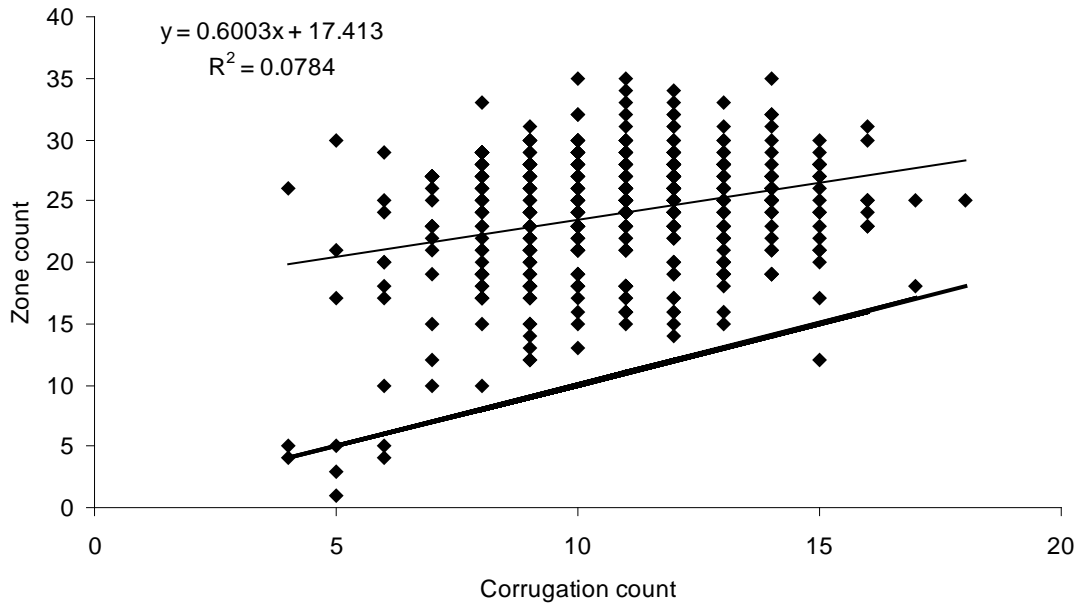


Figure 16: Comparison of thin section zone and whole otoliths corrugation counts. N = 453. The lighter line is the linear regression fit to the scatter plot and the regression equation for this fit is shown. The dark line indicates where a 1 to 1 relationship would lie.

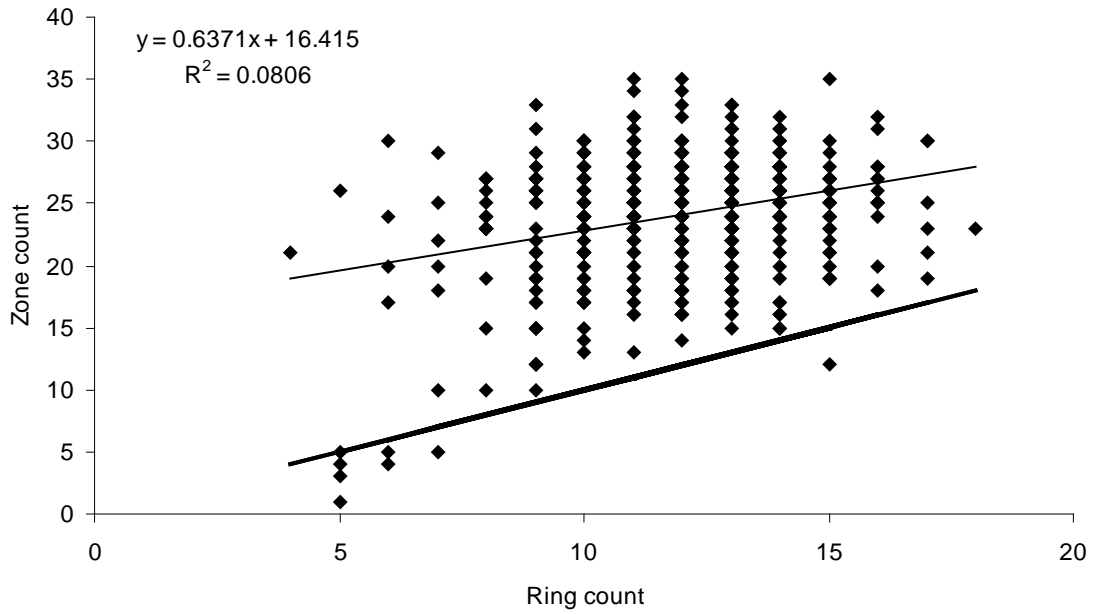


Figure 17: Comparison of thin section zone and whole otoliths ring counts. N = 453. The lighter line is the linear regression fit to the scatter plot and the regression equation for this fit is shown. The dark line indicates where a 1 to 1 relationship would lie.

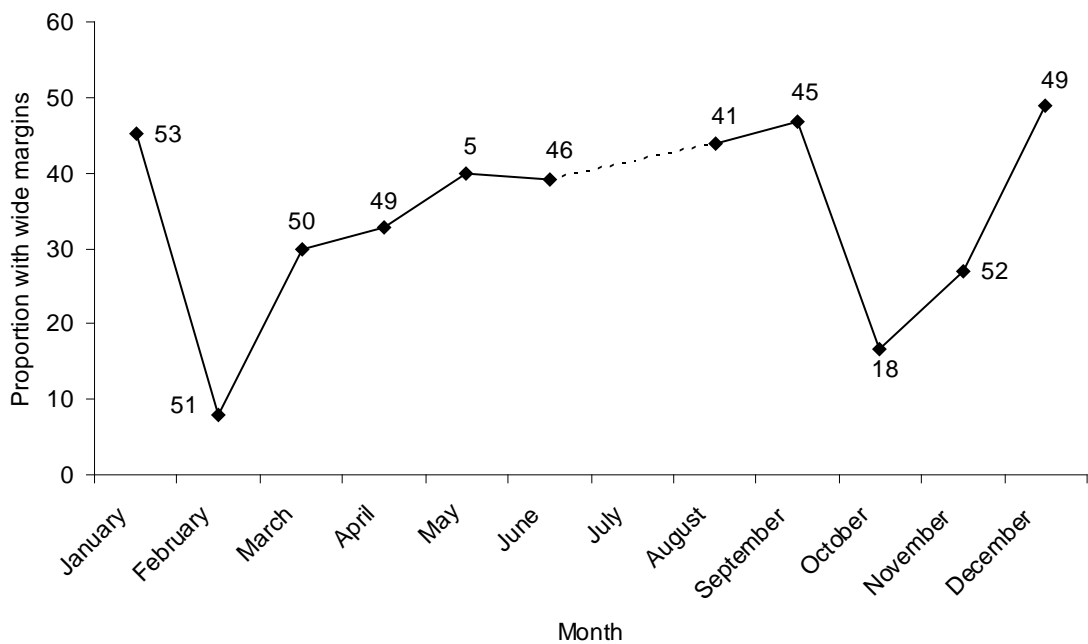


Figure 18: Proportion of otoliths with a wide marginal state by month. N= 462. The number of otoliths per month is shown.

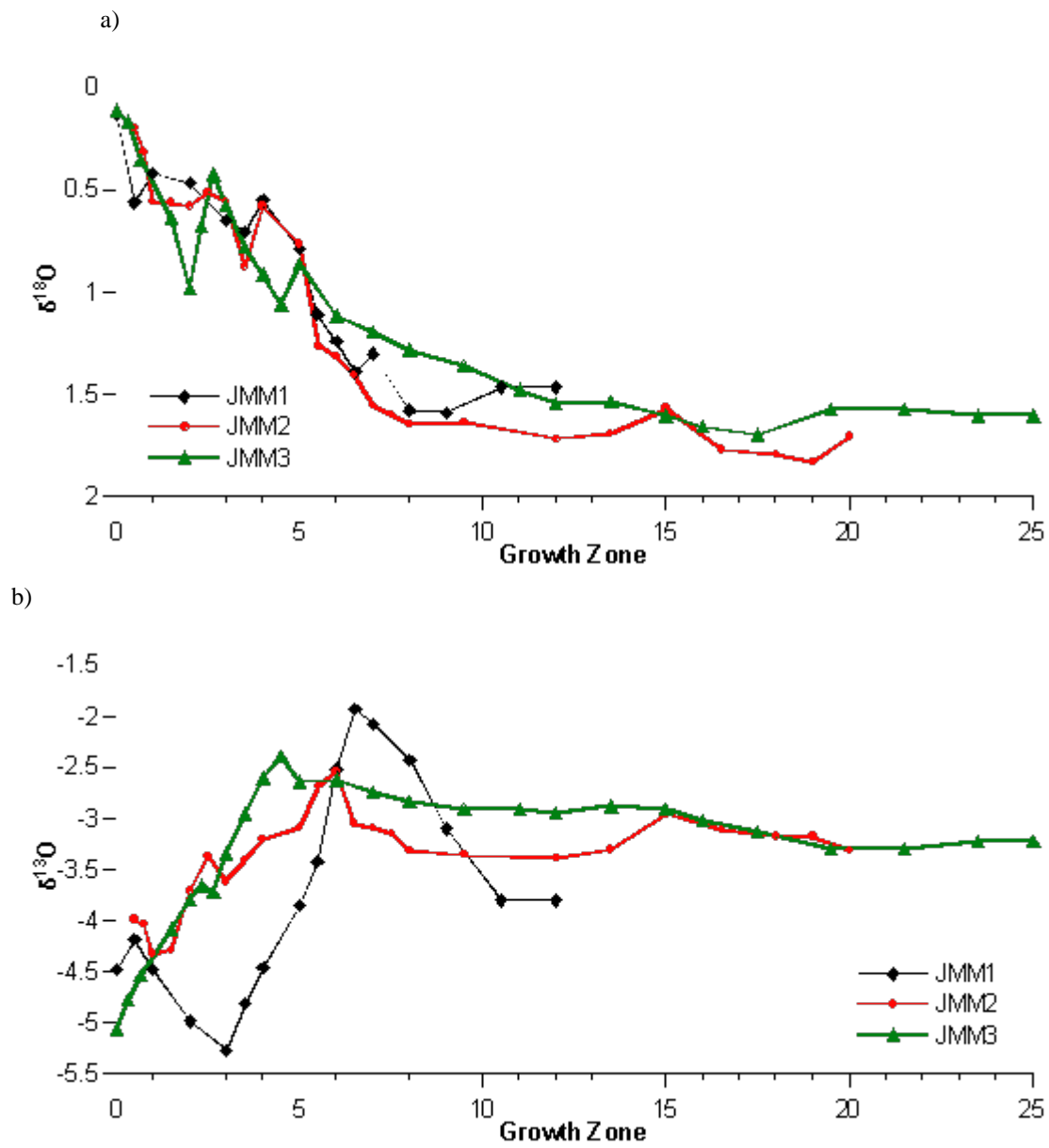


Figure 19: Temporal variation in a) $\delta^{18}\text{O}$ and b) $\delta^{13}\text{C}$ values of jack mackerel *Trachurus symmetricus murphyi* individuals.

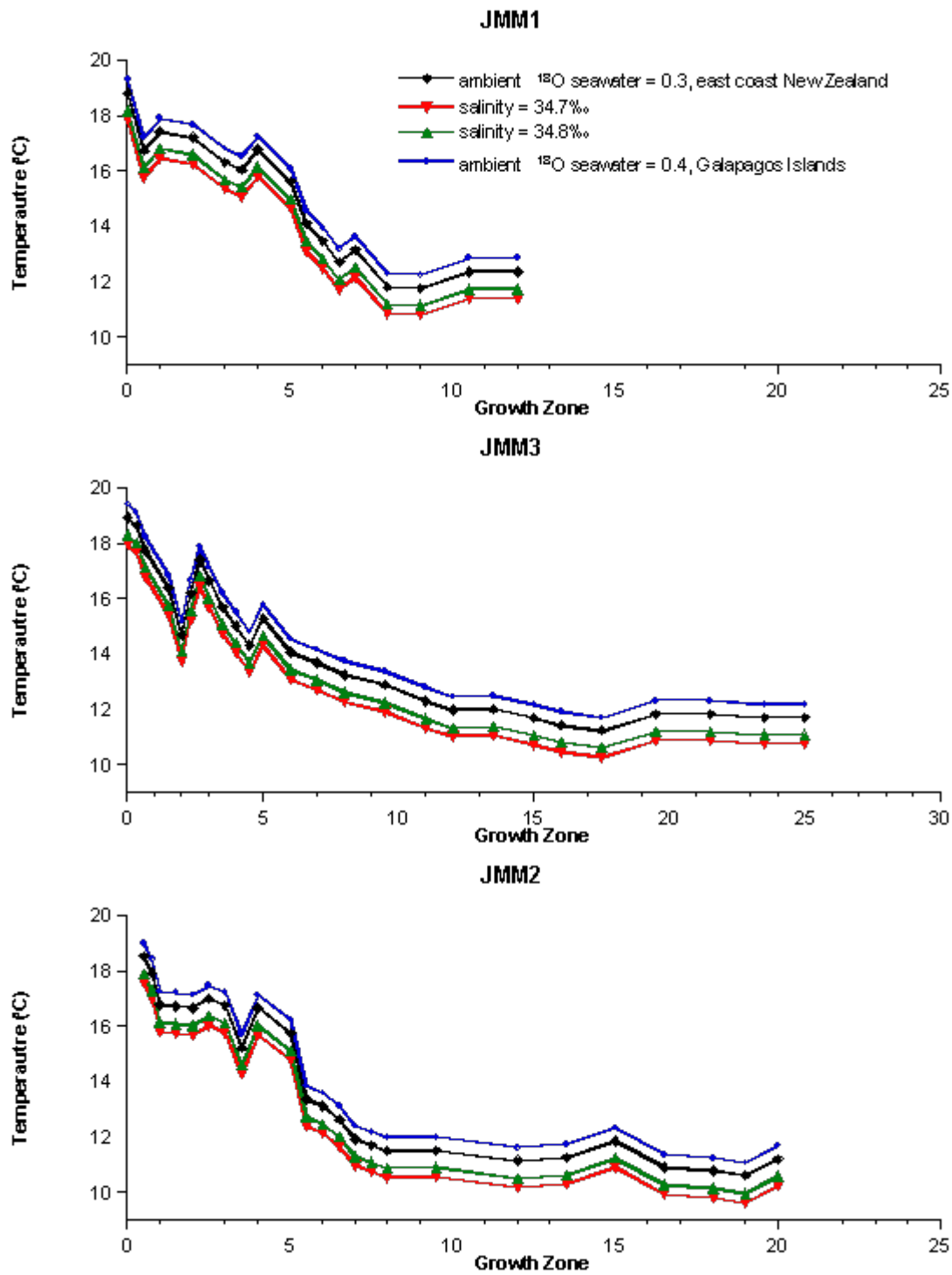


Figure 20: Otolith $\delta^{18}\text{O}$ predicted temperatures of individual jack mackerel *Trachurus symmetricus murphyi*.

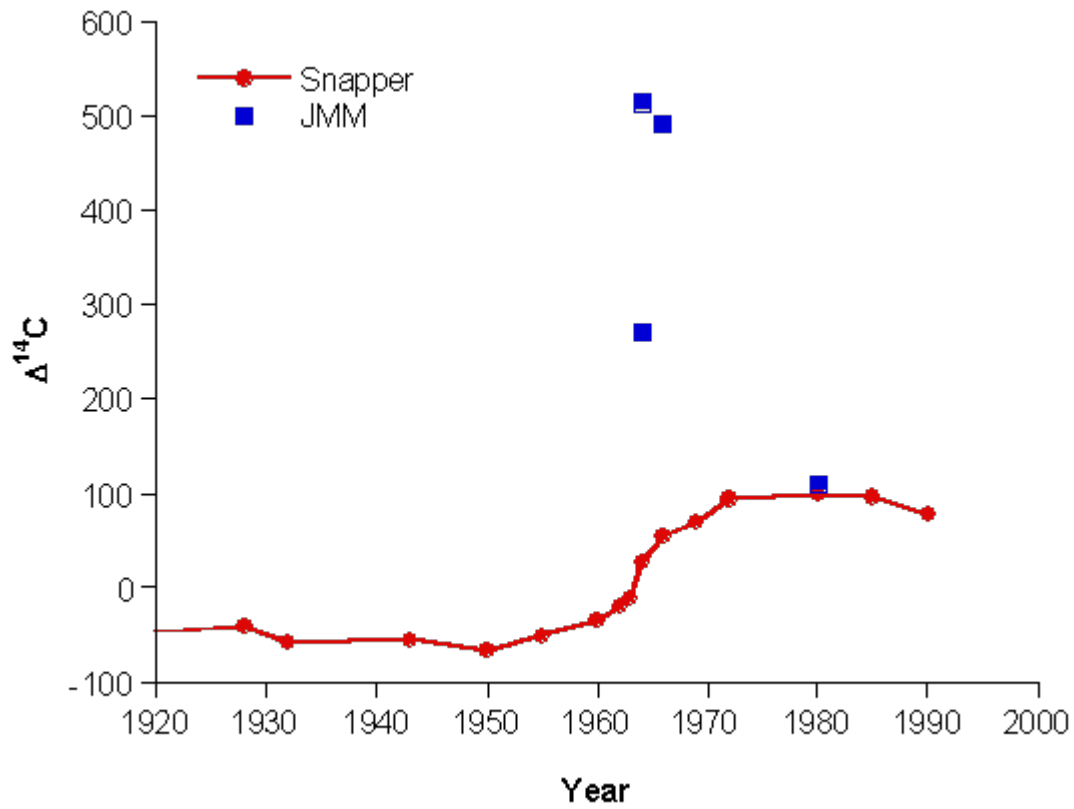


Figure 21: $\Delta^{14}\text{C}$ data for jack mackerel *Trachurus symmetricus murphyi*, plotted against year inferred from growth zone counts. Also shown is the reference snapper ^{14}C curve from Kalish (1993).

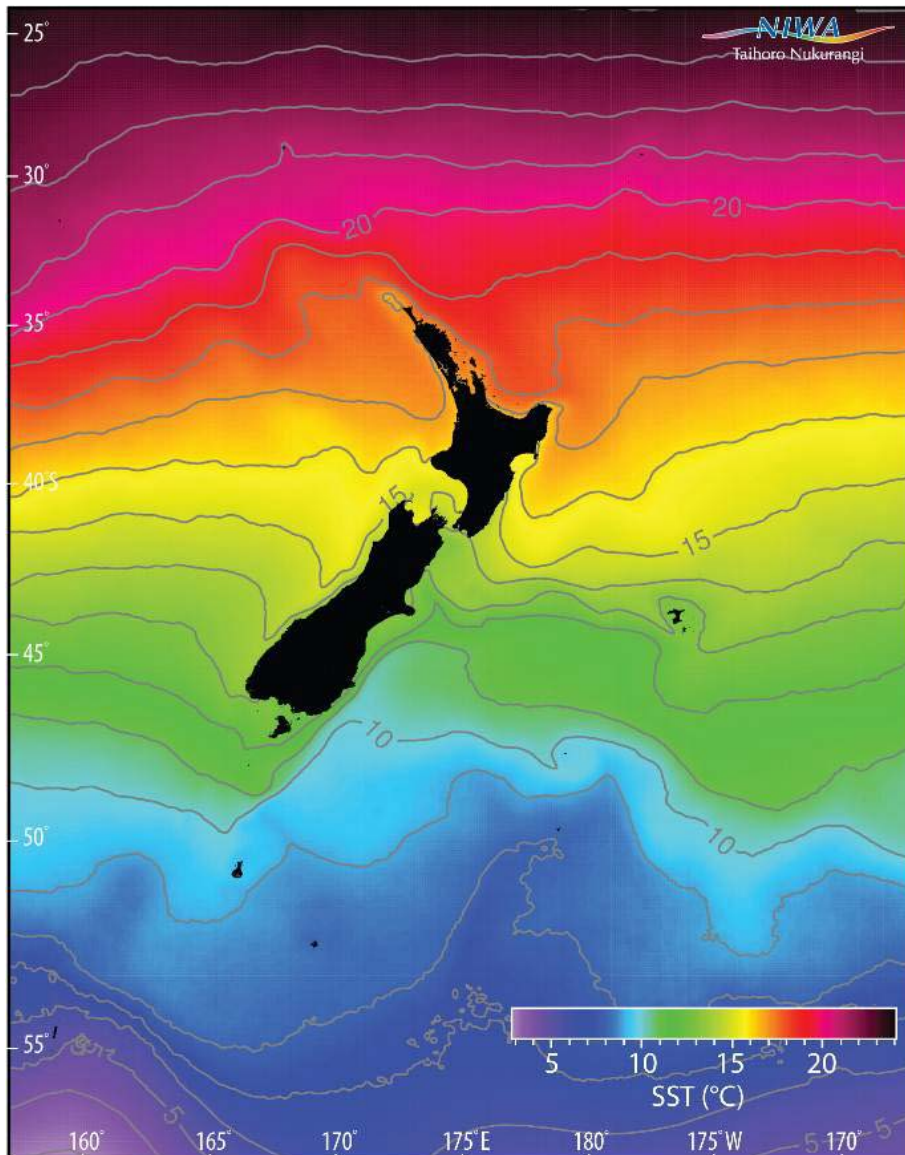


Figure 22: Contoured map of mean annual sea-surface temperature around New Zealand (from NIWA). Annual mean SST was taken from was estimated from an harmonic analysis of monthly composite data from the NIWA SST Archive (Uddstrom & Oien 1999). The analysis results in a high-resolution (9 km) data set showing a coherent relationship between the SST patterns and underlying oceanographic features (Uddstrom & Oien 1999, Hadfield et al. 2007). For the present work the analysis period covered the years 1993–2002. Because the NIWA climatology does not cover the entire analysis area, a similar climatology was also calculated from the CMB global $1^\circ \times 1^\circ$ SST dataset (Reynolds et al. 2002), also for the years 1993–2002. The two climatologies were interpolated onto a common 4 km grid and then blended using a function that introduced CMB data south of 55° S. (Prepared with the help of Mark Hadfield, NIWA).